Roadmap for flexible energy systems with underground thermal energy storage towards 2050

heatstore

High Temperature Underground

Thermal Energy Storage

HEATSTORE (170153-4401) has been carried out under the GEOTHERMICA – ERA NET Cofund aiming at accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximise geothermal heat production and optimise the business case of geothermal heat production doublets, and 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe.

This project has been subsidized through the ERANET cofund GEOTHERMICA (Project n. 731117), from the European Commission, RVO (the Netherlands), DETEC (Switzerland), FZJ-PtJ (Germany), ADEME (France), EUDP (Denmark), Rannis (Iceland), VEA (Belgium), FRCT (Portugal), and MINECO (Spain).

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About HEATSTORE

High Temperature Underground Thermal Energy Storage

The heating and cooling sector is vitally important for the transition to a low-carbon and sustainable energy system. Heating and cooling is responsible for approximately half of all consumed final energy in Europe. The vast majority – 85% - of the demand is fulfilled by fossil fuels, most notably natural gas. Low carbon heat sources (e.g. geothermal, biomass, solar and waste-heat) need to be deployed and heat storage plays a pivotal role in this development. Storage provides the flexibility to manage the variations in supply and demand of heat at different scales, but especially the seasonal dips and peaks in heat demand. Underground Thermal Energy Storage (UTES) technologies need to be further developed and become an integral component in the future energy system infrastructure to meet variations in both the energy availability and demand.

The main objectives of the HEATSTORE project are to lower the cost, reduce risks, improve the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (HT-UTES) technologies and to optimize heat network demand side management (DSM). This is primarily achieved by 6 new demonstration pilots and 8 case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. This will advance the commercial viability of HT-UTES technologies and, through an optimized balance between supply, transport, storage and demand, enable geothermal energy production to reach its maximum deployment potential in the European energy transition.

Furthermore, HEATSTORE also builds on experience from existing UTES facilities and geothermal pilot sites from which the design, operating and monitoring information will be made available to the project by consortium partners.

HEATSTORE has been carried out under the GEOTHERMICA – ERA NET Cofund and has the objective of accelerating the uptake of geothermal energy by 1) advancing and integrating different types of UTES in the energy system, 2) providing a means to maximize geothermal heat production and optimize the business case of geothermal heat production doublets, and 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe. The three-year project will stimulate a fast-track market uptake in Europe, promoting the development from demonstration phase to commercial deployment within 2 to 5 years, and provide an outlook for utilization potential towards 2030 and 2050.

The 23 contributing partners from 9 European countries in HEATSTORE have complementary expertise and roles. The consortium is composed of a mix of scientific research institutes and private companies. The industrial participation is considered a very strong and relevant advantage which is instrumental for success. The combination of leading European research institutes together with small, medium and large industrial enterprises, will ensure that the tested technologies can be brought to market and valorised by the relevant stakeholders.

Executive summary

The need for Underground Thermal Energy Storage in the decarbonisation of the heating and cooling sector

The heating and cooling sector is projected to remain the largest energy sector in the long-term under both business-as-usual and decarbonisation scenarios. The transition of the heating and cooling sector in Europe will depend strongly on the local, regional and national resources and priorities, but typically requires a mix of solutions: electrification with renewable power (wind, geothermal, photovoltaics ambient heat and others), renewable or low-carbon gases (e.g. hydrogen, biogas, synthetic gas) and renewable and waste heat sources for heating and cooling networks.

Underground thermal energy storage (UTES) involves the temporary storage of thermal energy in the subsurface. When excess heat is available this is transferred to a fluid and stored in the subsurface, and when the heat demand is high the stored heat is retrieved. Key high temperature UTES (HT-UTES) technologies were addressed in the HEATSTORE project. This includes aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), mine thermal energy storage (MTES) and pit thermal energy storage (PTES).

Thermal energy storage is already implemented in heating networks in the form of surface tanks storage and, although still highly limited, by UTES to support the use of surplus heat from industry and the implementation of renewable heat sources such as bio-Combined Heat and Power (CHP), geothermal, and solar energy. It provides the opportunity to integrate variable renewables (wind, solar) and baseload thermal heat sources (geothermal, biomass, surplus heat, ambient heat) in future sustainable heating systems.

Underground thermal energy storage has the potential to overcome short and long-term mismatch between demand and supply and therefore support the energy system by providing flexibility and reliability (i.e. adequacy) in a sustainable way. It is one of few long-duration storage technologies that can store vast amounts of energy up to tens of GWh per cycle.

The application of UTES can therefore help solve the problem of seasonality in heat demand and can reduce the carbon footprint of the energy sector. The technologies can be widely applied in energy

PTES and sun collector system in Marstal, Denmark. Source: Aalborg

infrastructures supplying sustainable and low carbon heat to industry, agriculture and district heating grids. Especially (district) heating networks with temperature ranges between 25 and below 100 °C are highly suitable. The main advantage of HT-UTES compared to low-temperature systems (~25 °C) is that the heat that is retrieved can be used directly for heating purposes and is suitable for more applications without a heat pump. For industrial heating networks with higher temperatures the technology could be applied in combination with heat pumps.

'Compared to other storage techniques UTES is economically competitive and it is compatible with many (local) renewable energy sources.'

UTES also provides valuable services to the electricity sector through sector coupling as it allows the absorption of electricity surpluses through power-to-heat solutions decoupling electricity production and heat demand from the short to seasonal timescale.

Compared to other storage techniques UTES is economically competitive and it is compatible with many (local) renewable energy sources. An especially interesting synergy is possible when heat and electricity sources with low marginal cost are available (e.g. geothermal, solar thermal, waste heat, environmental heat with heat pumps). It is an environmentally benign storage technique with limited use of rare earth materials required. The insulating properties of the subsurface allow for high volume and long-term storage with tolerable losses. Additional benefits of storing heat underground, although technology dependent, help reduce the spatial footprint of the future energy system.

Globally, low temperature UTES systems already account for several TWh of storage. The high temperature UTES options can best be defined as either early commercial or in the pilot/demonstration phase, depending on the technology. Over the next few decades these technologies and the project portfolio of HT-UTES systems could grow towards tens or hundreds of TWh of storage capacity in the EU energy system. HT-UTES has the potential to become the largest heat storage option and be an integrated part of the energy system in large parts of Europe. This entails that hundreds to even thousands of large-scale HT-UTES systems need to become operational in Europe in the next thirty years.

Drilling platform for HT-ATES in Middenmeer, The Netherlands. Source: ECW Energy

What is needed to progress Underground Thermal Energy Storage?

The main objectives of the HEATSTORE project were to lower the cost, reduce risks, improve the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (HT-UTES) technologies and to optimize heat network demand side management (DSM). This is primarily achieved by developing new demonstration pilots and detailed review of existing projects with distinct configurations of heat sources, heat storage and heat utilization.

The HEATSTORE project has made significant contributions to improve the technology and market readiness of the concepts (see summary exhibit). However, the HEATSTORE consortium has identified important actions that are needed to further accelerate the development and deployment of HT-UTES across Europe.

Technology & Innovation

It is critical for HT-UTES to further reduce technology risks and improve technical performance.
The HEATSTORE programme proved that demonstration sites are crucial to ensure that tested technologies can be brought to market and valorised by the relevant stakeholders. Learning by doing is the best way to gain skills and improve the knowledge base. For this purpose demonstration sites with extensive research programmes are key. An important lesson from HEATSTORE is that further innovation action is needed to improve the efficiency of a HT-UTES in the (first) operational years as this will enhance the business case and lower the financial risk. Some technology specific operational risks need further attention in order to improve their mitigation and to enhance investments in HT-UTES technologies. For all technologies reviewed by HEATSTORE, improved insight in the subsurface suitability for the different HT-UTES technologies is needed across Europe to lower the threshold for spatial planning agencies and heat network developers to include HT-UTES as part of their energy system design. Finally, any HT-UTES project needs optimal integration in the heat grid in such a way that it improves the flexibility and sustainability of the heat network and increases its cost-efficiency.

> ‘Learning by doing is the best way to gain skills and improve the knowledge base. Demonstration sites with extensive research programmes are key.’

PTES site in Høje Taastrup (Denmark) with new liner material that can withstand a constant temperature of 90°C. Source: PlanEnergi

Market & Economics

A key insight observed within the HEATSTORE project and in literature is that large-scale thermal storage solutions are very cost-effective. However, actions are needed to further lower the project costs and investment risks for large-scale market development of HT-UTES in Europe. HEATSTORE has helped to recognize that every underground thermal energy storage project is unique, but that a common approach can help to establish a robust business case. Establishing a long-term learning curve to further drive down investment and operating cost of HT-UTES technologies is warranted. This requires research and innovation, but also learning by doing so that replication can help improve project economics (CAPEX and OPEX). As with other energy storage technologies it is critical to get the revenue pillar of the business model right. This is achieved by matching a revenue model for the value that a storage project provides to the system and to individual actors in the value chain. HT-UTES projects have site specific value propositions and thus require an approach to identify, stack and valorise multiple propositions. In many situations the revenues are not sufficient and thus (policy) incentives are required to achieve a positive business case. Finally, the ownership model and market structure shape the business model for HT-UTES. This means that clarity of roles and responsibilities is required and to find ownership and contractual relationships between partners that optimally fit with the business case.

Society & Environment

Some environmental impacts of HT-UTES systems are inevitable; the local extraction and injection of groundwater and the thermal effects inherently induce physical, chemical and microbial changes. The environmental impacts are highly case- and location specific and need to be evaluated in the early phase of an HT-UTES project development. A key learning is that projects need guidelines to evaluate and mitigate environmental impacts and robust monitoring programmes will support the containment of risks. In order to build trust and engagement among stakeholders, including the public, it is important to create awareness in HT-UTES development in general and in an early stage of HT-UTES projects specifically. It is then needed to provide balanced information on environmental risks and benefits. One possible solution could be to draft a spatial planning for the subsurface to start raising awareness and to reduce competition of subsurface space in future plans.

Policy & Regulations

The key action is to start strategy formation on HT-UTES in local, national and EU energy system planning. And facilitate the achievement of these strategies by the timely development of a supporting regulatory and policy framework. The integration of HT-UTES technologies in future energy scenarios and energy system planning will allow the demonstration of the crucial role that HT-UTES can play in the decarbonatization of the heat sector. This will support the development of local and national roadmaps for a sustainable heating and cooling supply.

Including HT-UTES in energy- and climate strategies of cities, industry clusters, regions, member states and Europe as a whole, requires awareness and capacity building among stakeholders at different geographical levels and across industry, science, governments and the public. The local and regional governments have been proven very important as heating and cooling networks span across their jurisdiction. This also requires early local public stakeholder engagement in specific HT-UTES projects for successful, large-scale deployment of HT-UTES. And when included in a robust communication and engagement strategy towards all relevant stakeholders, this can be a crucial support in the creation of awareness.

HT-UTES projects are an integral part of large and long-term infrastructure investment decisions that require investment certainty for project developers. Simple and clear support schemes and an enabling market framework are required to support stakeholders in the development of HT-UTES systems.

Furthermore, The HEATSTORE research programme studied existing regulatory frameworks of a sample of EU member states identifying existing regulatory frameworks and potential barriers. The recommendation is that clear regulations specifically for high temperature UTES technologies need to be developed to smoothen the large-scale deployment.

Short term tangible actions for tomorrow

The need for progress and inclusion of thermal storage in a comprehensive approach to energy storage has recently been highlighted by the European Parliament. A clear recognition that demands for further actions on the short and longer term. Considering that the timeline from project idea up to an operational system spans several years, large-scale deployment of this technology should start now. Specifics in geology and surface restrictions may provide favourable conditions for specific HT-UTES technologies and exclude others. Therefore, a portfolio of HT-UTES technologies needs to be available and be technologically advanced to enable location specific needs to be identified and addressed. This requires urgent action:

1. **Strong need for awareness and strategy on local, national and European level**
2. **Help early movers with the financial de-risking and support schemes for early commercialisation**
3. **Launch the European Underground Thermal Energy Storage Alliance**

Figure 1 HEATSTORE contributions to the development and deployment of high temperature underground thermal energy storage

Understanding subsurface conditions

- Insight into value of pre-feasibility drilling before projectstart to optimize design of UTES
- New characterisation tools to better understand the subsurface and de-risk UTES projects
- Better maps of UTES potential across EU countries

Modelling subsurface dynamics

Enhanced models to simulate subsurface performance of UTES technologies

Heating system integration & UTES design optimisation

Heat grid Integration: inclusion of UTES performance (proxy) modelling and demand side response controller in heat grid optimisation software packages for design and operation. To reduce costs, improve efficiency and reduce emissions.

Demonstration and monitoring

Succesfull start up of new UTES projects within the project duration and enhanced monitoring in existing UTES projects.

Best practices and replication

Start of an international UTES community to share learnings of successes and challenges on:

- Design & System integration
- Business model
- Regulatory framework
- Stakeholder perception & engagement
- Monitoring & Environ-mental performance

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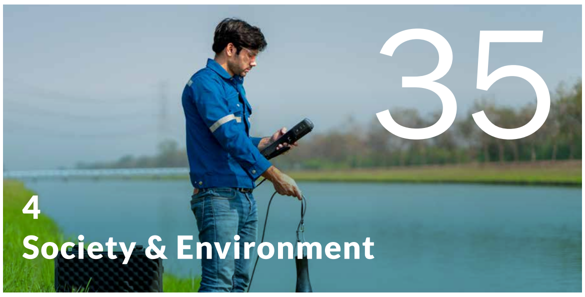
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1.1 Background and need for heat storage

1.1.1 Sustainable power and heat transition requires thermal storage

In order to fight climate change and limit its impacts on our environment, the global energy mix is currently shifting from fossil fuels towards renewable energy. The deployment of renewable energy sources (RES) for both power and heat production is accelerating in Europe, a trend that will continue to achieve the ambition of becoming the world's first climate-neutral continent.

Despite its magnitude and importance in the European Union's energy markets, the heating and cooling sector is often overlooked compared to other energy sectors in energy transition scenarios and policies. Heating and cooling in buildings, businesses and industry consume around half of the energy produced and used in the European Union. The residential sector is the largest with 45% of energy for heating and cooling followed by 37% in industry and 18% in the service sector. Heating and cooling currently relies (in terms of flexibility and energy volume) on fossil fuels (85%).[1] The role of natural gas is evident here. With the current storage capacity of more than 1 PWh and 68% of all EU gas imports related to heating and cooling it showcases the EU's reliance on fossil fuels related to security of supply in case of cold spells and supply disruptions.

The variations in both the demand and availability of renewable energy raise challenges in terms of operational variability and balancing. In comparison to fossil fuels, renewable energy sources are less flexible as fossil fuels can be switched on/off according to the

Figure 2 Heating and cooling sector decarbonisation solutions

Electrification

Application: residential and service sector for low temperature heating and cooling; high temperature electrification in development (e.g. for industry with HT heat pumps)

Sourcing: now fossil dominated towards renewables and low carbon electricity generation (PV solar, wind, tidal, hydro, geothermal, nuclear, biomass)

Efficiency: Energy efficiency gains with heat pumps

Power Grid: Lower efficiency in cold periods: pressure on the European power system in cold spells

Storage: Long duration storage of electricity difficult and costly; small scale thermal storage in combination with heat pumps in development/pre- commercial

Hydrogen/renewable gases

Application: on the shorter term for high temperature heating for industry. Possible but considerable uncertainty for application in residential and service sector (e.g. pure or via blending with natural gas); more likely limited role and on long term for low temperature heating.

Sourcing: low carbon and green hydrogen production still at limited scale available; future from blue hydrogen (natural gas reforming), green hydrogen (electrolysis); biogas production possible, import from outside EU possible

Efficiency: Energy losses during hydrogen production; limited losses during transport and storage.

Gas Grid: conversion of existing gas grid with very high energy transport capacities; blending with natural gas possible

Storage: large capacity and long-duration storage capacity possible in surface facilities (terminals) and subsurface (caverns, reservoirs) at low cost and high efficiency compared to electricity storage

Heating and Cooling networks

Application: heat networks for both industry and residential/service sector; many high temperature (>100 °) sourced heating grids exist, trend towards low temperature (4th gen) heating networks.

Sourcing: currently ranging from fossil fueled networks to best practices with very high share of renewables; large future potential for geothermal, solar thermal, biomass, industrial waste heat, heat pump sourcing. Often local sourcing of heat

Efficiency: transport losses can be high; conversion losses from fuels to heat; strorage efficiencies from 50-95% depending on technology

H&C networks: often local to regional networks, private and public owned (also communities)

Storage: large capacity and long-duration storage capacity possible in surface facilities and subsurface at low cost compared to electricity storage fluctuating energy demand. Therefore, the energy transition is associated with a compelling need for additional options to increase flexibility and secure the supply of heat. This can be provided by dispatchable production, demand side response, enhanced transport infrastructure, sector coupling (conversion) and energy storage.

The heating and cooling sector is projected to remain the largest energy sector even in the long-term under both business-as-usual and decarbonisation scenarios by 2030 and 2050.[2] The transition of the heating and cooling sector in Europe will depend strongly on the local, regional and national resources and priorities, but typically requires a mix of solutions: electrification with renewable power (wind, geothermal, solar, ambient heat and others), renewable or low-carbon gases (e.g. hydrogen, biogas, synthetic gas) and renewable and waste heat sources for heating and cooling networks (Figure 2).

These three decarbonisation solutions typically have different strategies to maintain balance, flexibility and security of supply in the respective infrastructures for electricity, renewable gases and heat. One specific challenge that should be resolved is the typical seasonal profile of demand in the heating sector in Europe.

While electricity storage has attracted a lot of focus in recent years in order to balance power grids, and underground hydrogen storage could provide very large flexibility in the future gas grid, thermal energy storage plays a similar inevitable role in the heating and cooling sectors, and beyond.

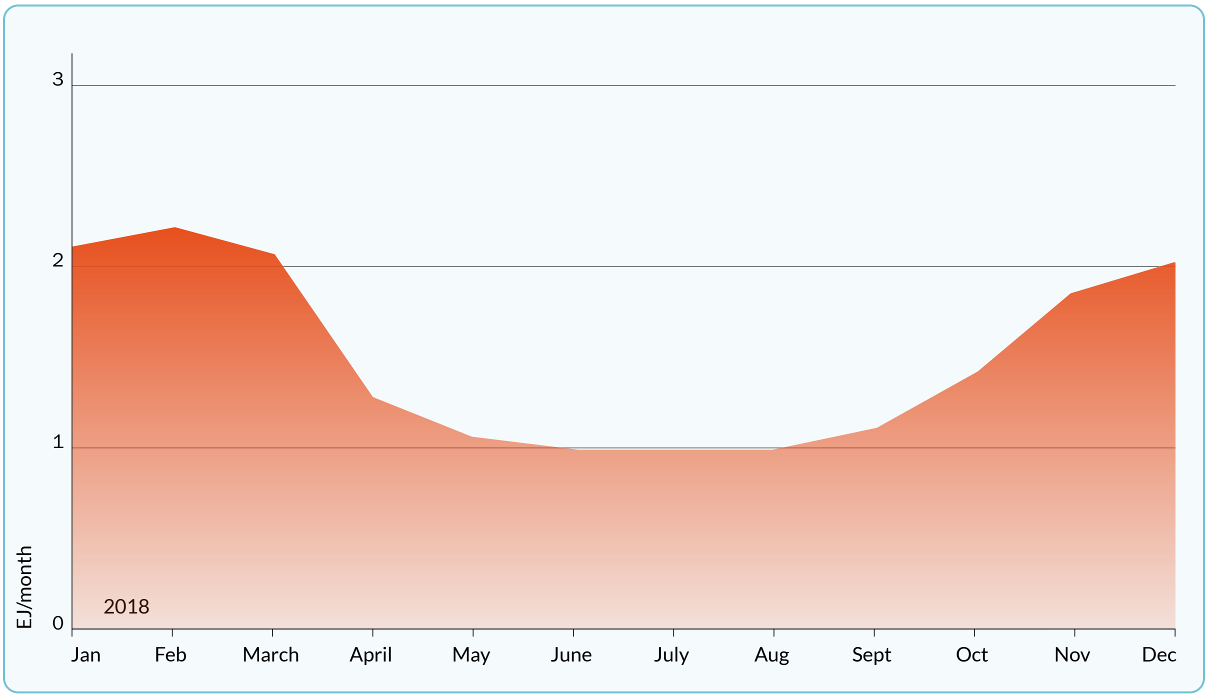
Seasonal energy storage is needed to support the use of surplus heat from industry and the utilization of renewable heat sources such as bio-Combined Heat and Power (CHP), geothermal, and solar energy. It provides the opportunity to integrate variable renewables (wind, solar) and baseload thermal heat sources (geothermal, biomass, surplus heat, ambient heat). This contributes to short and long-term flexibility in the heating and cooling sector. It also provides valuable services to the electricity sector through sector coupling as it allows to absorb electricity surpluses through power-to-heat solutions decoupling electricity production and heat demand from the short to seasonal timescale. All in all, it provides important contributions to reducing the carbon footprint of energy sector.

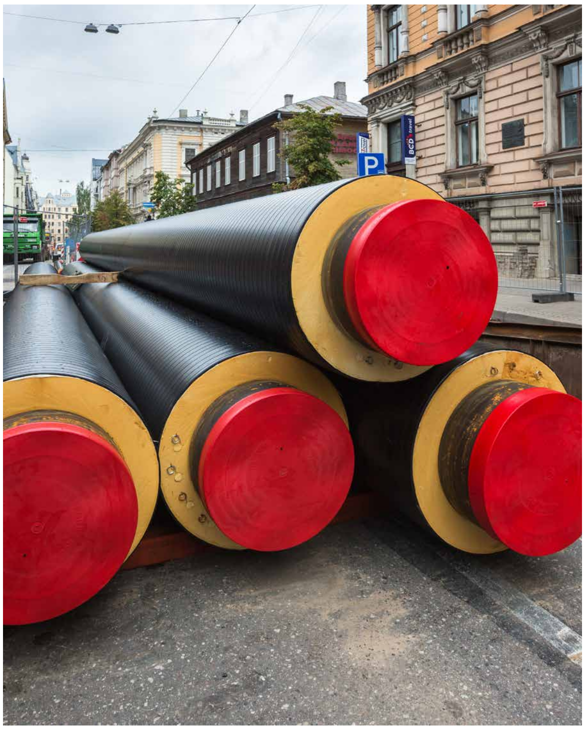
Thermal energy storage is currently implemented in heating networks in the form of surface tank storage which is limited in capacity and hence does not allow for long duration (seasonal) and large-scale heat storage.

Underground Thermal Energy Storage (UTES) has the distinct advantage that it provides a smart and replicable solution for the 'bathtub challenge' (Figure 3) for regions that have a seasonal dip and peak in heating demand. It offers large-scale (>10 GWh) storage capacity per site, which is difficult to achieve with other heat storage technologies, or even with other energy storage options in general. Additionally, HT-UTES techniques benefit from a typically lower range of storage costs.[3]

Figure 3 The 'bathtub' challenge: how are we going to meet the heating demand in Europe with a distinct seasonal profile without fossil fuels but with the same security of supply? Here the bathtub is represented by the Natural gas demand in Europe.

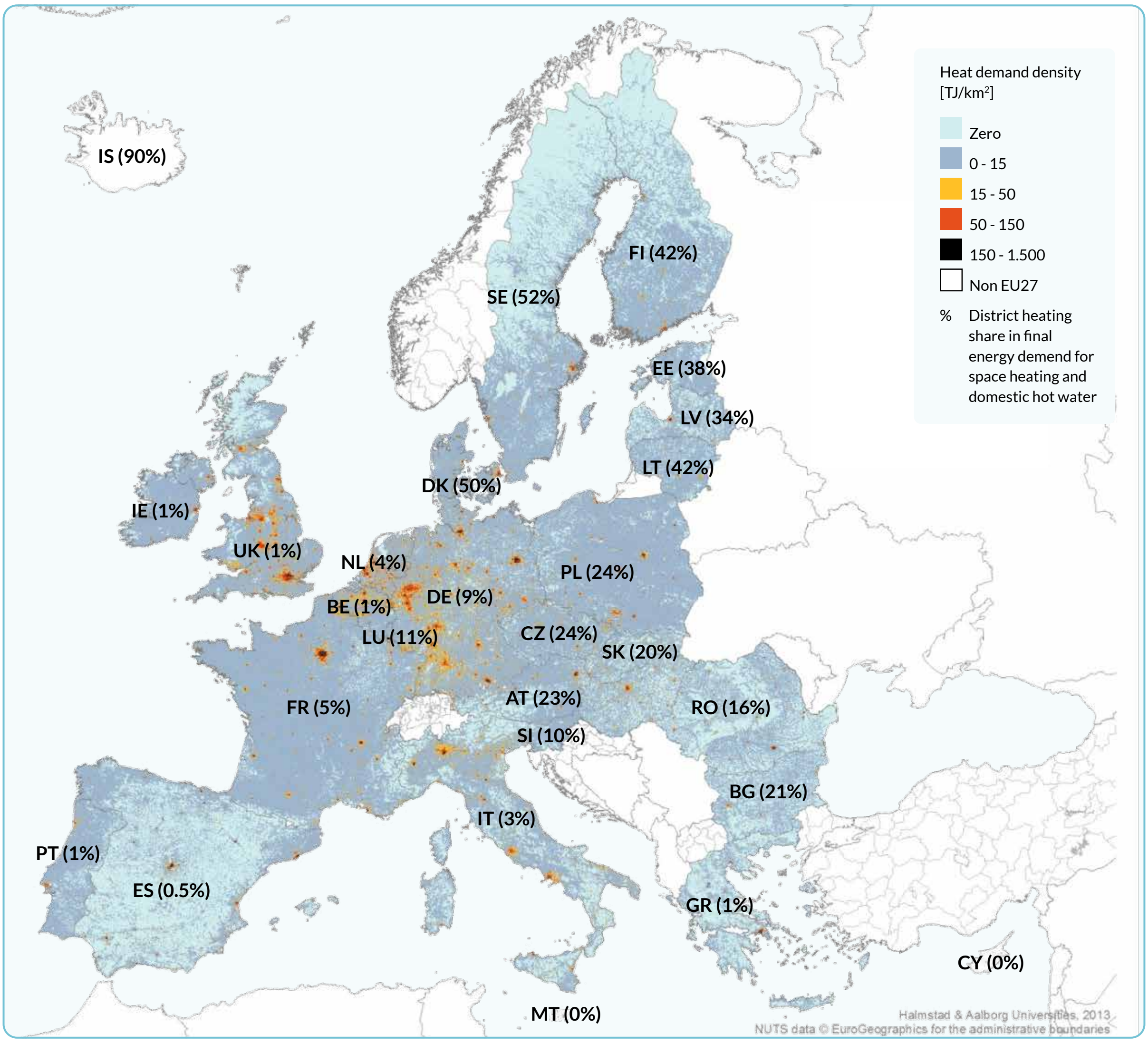
Source: Eurostat figures published in EUROBASE as of 26/04/2019.





> ‘The heating and cooling sector is projected to remain the largest energy sector even in the long-term under both business-as-usual and decarbonisation scenarios by 2030 and 2050’

Figure 4 European heat demand density and district heating share in final energy demand for space heating and domestic hot water.
Graphic adapted from: Connolly et al. (2013)[4] and Mathiesen et al. (2019)[5]



The main advantage of high temperature UTES (HT-UTES) with a storage temperature between ~25°-90°C, compared to low temperature systems (~25 °C) is that the heat that is retrieved can be used directly for heating purposes and is suitable for more applications without a heat pump. For industrial heating networks with higher temperatures the technology could be applied in combination with heat pumps. The HT-UTES technologies can then be widely applied in energy infrastructures supplying sustainable and low carbon heat to industry, agriculture and district heating grids. Especially (district) heating networks with temperature ranges between 25 and below 100 degrees Celsius are highly suitable.

District heating currently supplies 12% of space heating and domestic hot water demand for buildings in Europe[6]. There are more than 12,000 district heating networks in Europe, supplying more than 10% of total European heat demand with an annual turnover of €27-32 billion through 2.2 EJ (610 TWh) of heat sales.[7,8] In some countries the share of district heating covers more than 50% of demand. Countries with large contributions from district heating are typically Northern Europe (Scandinavia), Central and Eastern Europe (Figure 4).

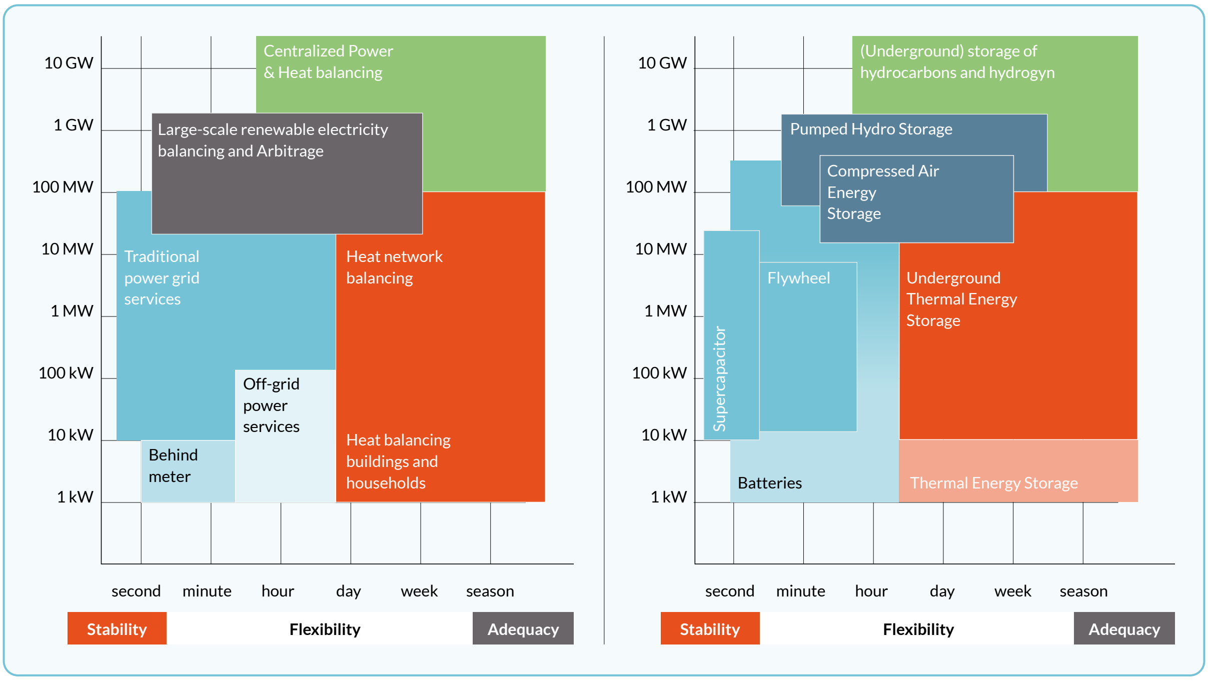
Furthermore, as HT-UTES is best positioned to support heating networks at the 25-100°C temperature range, possibly higher, this indicates it could play a very important role in facilitating the decarbonisation of Europe's low-temperature industrial demand summing to 574 TWh.[9]

"Climate change and environmental degradation are an existential threat to Europe and the world. To overcome these challenges, the European Green Deal will transform the EU into a modern, resource-efficient and competitive economy, ensuring:

- **No net emissions of greenhouse gases by 2050**
- **Economic growth decoupled from resource use**
- **No person and no place left behind**

One third of the 1.8 trillion euro investments from the NextGenerationEU Recovery Plan, and the EU's seven-year budget will finance the European Green Deal."[10]

Figure 5 Energy system services and storage options mapped according to their power (Watt) and relevant timescales for charging and discharging. Colours coding indicate in which infrastructure system the storage technology is implemented: blue = electricity grids, green = (renewable) gas infrastructure; orange is heat networks. *Source TNO, inspired by IEA.*



1.1.2 Application of underground thermal energy storage

Underground thermal energy storage (UTES) involves the temporary storage of thermal energy in the subsurface. When excess heat is available this is stored by heating the soil or a fluid in the subsurface and when the heat demand is high the stored heat is retrieved. Various high temperature UTES (HT-UTES) technologies were addressed in the HEATSTORE project. These include aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), mine thermal energy storage (MTES) and pit thermal energy storage (PTES). Other options outside the scope of the HEATSTORE project are Cavern Thermal Energy Storage (CTES)[11] and Underground Tank Thermal Energy Storage (UTTES)[12]. A short explanation of the concepts and their strengths and weaknesses is provided in Figure 6 and Figure 7.

The selection of a suitable technology depends on the required volume of the storage site, the heat grid specification and the required surface and subsurface conditions/characteristics. Thermal energy can be supplied by many different sources. In principle, any source that has either highly fluctuating energy production (e.g. thermal solar energy), or provides a more continuous amount of energy throughout the year, even when the energy is not needed (e.g. geothermal energy systems or industrial waste heat), can benefit from large-scale HT-UTES. From a business case perspective, sources with low marginal production costs are necessary to build a promising business case. The integration of HT-UTES in a heat network with a sustainable heat supply contributes to increasing the efficiency of renewable and low carbon energy sources. Additionally, HT-UTES can add much needed operational flexibility to energy systems at large, as part of a storage technology portfolio servicing different energy capacities, time dimensions and energy grids (Figure 5).

'HT-UTES can add much needed operational flexibility to energy systems at large, as part of a storage technology portfolio servicing different energy capacities, time dimensions and energy grids.'

The main objectives of the HEATSTORE project are to lower the cost, reduce risks and improve the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (HT-UTES) technologies and to optimize heat network demand side management (DSM). This is primarily achieved by 6 new demonstration pilots and 8 case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. This will advance the commercial viability of HT-UTES technologies and, through an optimized balance between supply, transport, storage and demand, enable that geothermal energy production can reach its maximum deployment potential in the European energy transition.

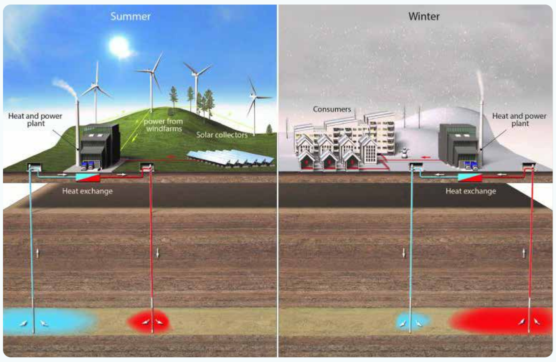
Figure 6 Qualitative comparison of HT-UTES technologies.[13]

Comparison of HT-UTES concepts	HT-ATES	HT-BTES	HT-PTES
Storage medium	Groundwater/sediments	Groundwater/sediments/ rock formation	Water
Subsurface requirements	XXX	XX	X
Required pre-investigation	XXX	XX	X
Maximum storage capacity	XX(X)	X	XXX
Storage volumes	XX	XX	XX
Space requirements	X	X	XXX
Peak load response	X(X)	X	XXX
Investment costs	X(X)	XX(X)	XX(X)
Maintenance	XXX	X	X(X)
Environmental interaction	XXX	XX	X

Current assessment/interpretation MTES - first of its kind, not included High: XXX Medium: XX Low: X

- HT-UTES supports the transition to a sustainable heat supply;
- It enables more efficient use of (local) sustainable heat sources;
- It has the capacity to store large quantities of thermal energy (potentially >10 GWh) over a large period in order to match seasonal supply and demand;
- It increases operational flexibility of energy systems;
- Depending on the technology, it has the capability to serve different energy systems, from large-scale district heating and cooling networks and industrial applications, to small scale systems for commercial buildings and household dwellings.
- It can provide flexibility to the electricity grid via electric boilers and heat pumps allowing surplus electricity to be efficiently stored as heat for later use in heating and cooling networks (power-to-heat).
- HT-UTES can store energy on different timescales: days, weeks or even months.
- Peak shaving and heat storage can help to balance demand and supply to make better use of infrastructure and assets (e.g. increase full load hours for geothermal and solar heat sources).
- HT-UTES benefits from a typically lower range of storage costs compared to other heat/ energy storage technologies.[14]

Figure 7 How does it work? Different underground thermal energy storage technologies explained.[15, 16, 17, 18, 19, 20]

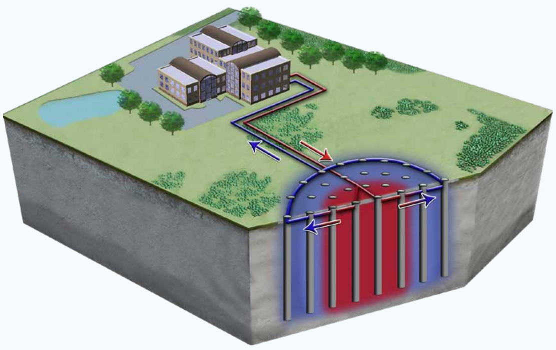


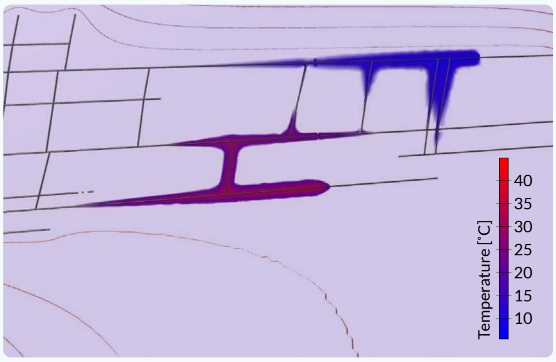
Aquifer Thermal Energy Storage

ATES can take place by injection and later re-production of hot water in aquifers in both shallow and deep geological formations. The aquifers can be both unconsolidated sand units, porous rocks like sandstones or limestone or fractured rock formations. It is an open system using geothermal or water wells and storing the heat in the groundwater and in the formation around it.

Pit Thermal Energy Storage

Hot water is stored in very large (multiple) excavated basins with an insulated lid. Sides and bottom are typically covered by a polymer-liner, but can also be made of concrete.





Borehole Thermal Energy Storage

The natural heat capacity in a large volume of underground (unconsolidated) soil or rock is used to store thermal energy with or without groundwater as the storage medium. It typically has several closely spaced boreholes, between 50 and 200 m deep; they act as heat exchangers to the underground, usually in U-pipe form.

Mine Thermal Energy Storage

Mine water of abandoned and flooded mines is used as a storage medium for high temperature storage. The mine water can also be used as an ambient energy source in combination with heat pumps.

1.2 Current role of underground thermal energy storage

1.2.1 Aquifer Thermal Energy Storage

In 2018, more than 2800 ATES systems were or have been in operation worldwide. Approximately 2500 of these systems are located in the Netherlands, 220 in Sweden, 55 in Denmark and 30 in Belgium (Figure 8).[21]

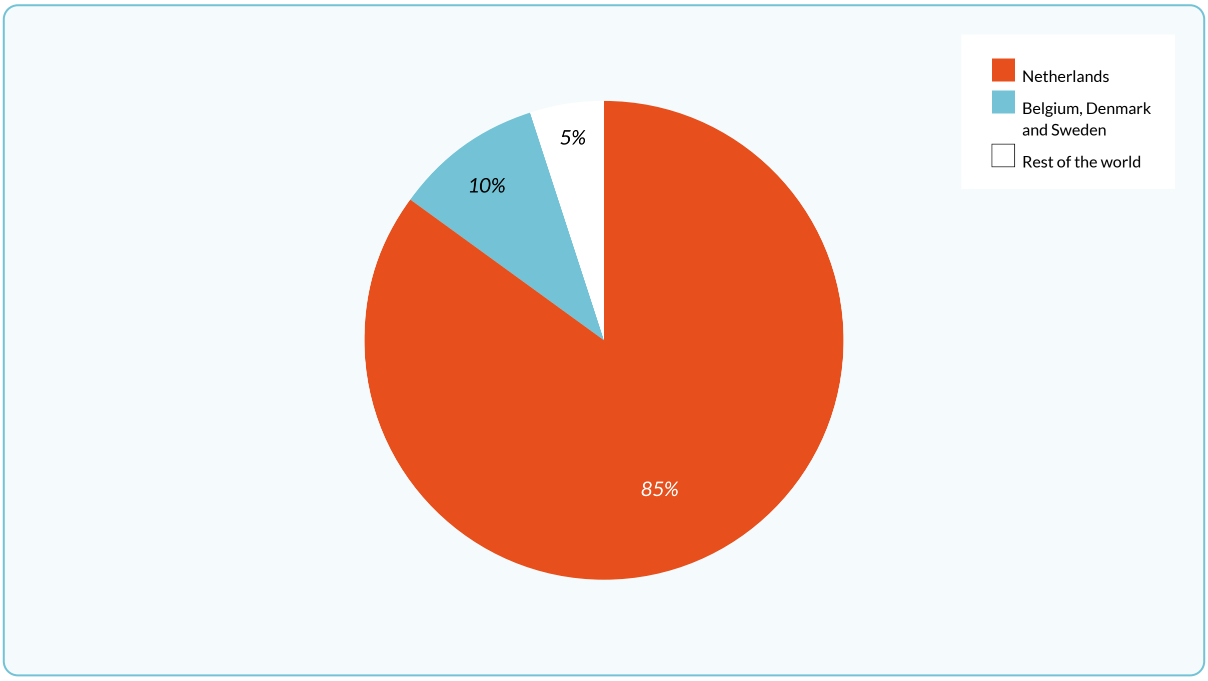
In total, these ATES systems provide more than 2.5 TWh of heating and cooling per year, which equals the thermal energy consumption of approximately 150,000 households.[21] Although early ATES projects included storage at temperatures higher than 40°C (HT-ATES), most systems are associated with individual buildings with a heat pump and supply both heating and cooling, and hence operate on low temperatures. One of the world's largest ATES system is located at Stockholm's Arlanda airport. The aquifer, which is used for both cooling and heating, has a capacity of 10 MW. On an annual basis, the project reduces the airport's energy use by up to 20 GWh.[22] In several countries, including China, the number of ATES systems is increasing rapidly and an increasing number of countries are showing an interest in the technology.[21]

In the HEATSTORE project, 7 previously developed HT-ATES systems were identified, with 4 established from 1976 to 1982 in the USA, Switzerland and Denmark and 3 established from 1987 to 1998 in the Netherlands and France. The HT-ATES systems were all explorative in nature or were developed as demonstration sites. All of them were later closed down due to either ending of test period, supply/demand mismatch, technical problems or insufficient recovery efficiency. Two HT-ATES systems in Germany established in 1999 and 2004 are still in operation and well-functioning. One of the sites stores waste heat from a power plant for later reuse in a district heating system. Feasibility studies have previously been carried out for two HT-ATES systems in Germany and the Netherlands, and in the HEATSTORE project three HT-ATES demonstration systems have been or are being established in Switzerland and the Netherlands (of which the latter is operational from 2021 onwards). Two systems in Switzerland are based on storage of surplus heat from waste combustion feeding into district heating systems and the system in the Netherlands is based on storage of surplus geothermal heat feeding into a local grid for the horticultural industry.

1.2.2 Borehole Thermal Energy Storage

Low temperature BTES systems are operated in many countries all over Europe.[23, 24, 25] For HT-BTES 12 systems established from 1983-2012 have been identified in Germany, Sweden, Denmark, Canada, Finland, Belgium, Czech Republic and the Netherlands. One was closed down after 6 years of operation due to a lower recovery efficiency than had been expected, and one was a test facility which planned to be operational for less than one year. The remaining 10 systems are assumed to still be in operation. Eight of the systems are based on seasonal storage of solar heat and four are based on waste heat from industry

Figure 8 Geographic distribution of current ATES systems.[21]



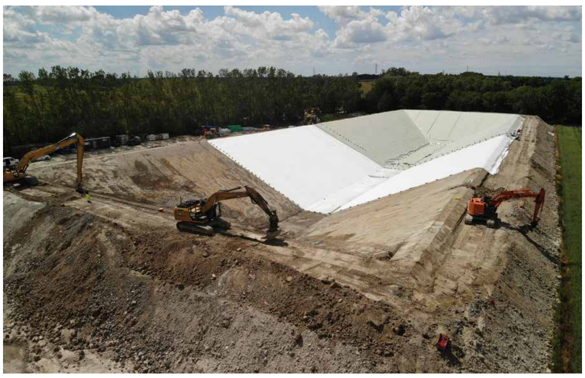
'In 2018, more than 2800 low temperature ATES systems were or have been in operation worldwide. These systems provide more than 2.5 TWh of heating and cooling per year.'

or power production. All of the systems except the test facility have been designed to provide heat for larger office-type or factory buildings (3) or smaller local district heating networks of 30-300 domestic homes (7) and one larger district heating network of ca. 1500 domestic homes. On average the observed recovery efficiency of the stored heat has been around 50%, but for some of the combined solar heat and BTES systems the overall system efficiency is very high with solar supplying 80-90% of the total energy consumption. In the HEATSTORE project, a HT-BTES demonstration system is planned in France by converting a low-temperature BHE (borehole heat exchanger)-field into a HT-BTES for storage of surplus heat.

1.2.3 Pit Thermal Energy Storage

In Denmark, the combination of solar heat and Pit Thermal Energy Storage (PTES) in district heating networks has proven successful. Five large-scale PTES systems have been established since 2010 and are still in operation today, ranging from 60,000 m^3 (of water) to 205,000 m^3. Others are under construction or in the planning phase. In Høje Taastrup, a 70,000 m^3 daily storage is being built in 2021 and will be coupled to the main district heating network of greater Copenhagen to act as a flexible heat storage and help obtain consumption/production energy balance. Other seasonal heat storages have been implemented

Construction of PTES site in Høje Taastrup, Denmark.
Source: HTF Denmark



worldwide, for instance, a 15,000 m^3 PTES in 2018 in Tibet. The recovery efficiency for some of the systems has been seen to be as high as from 70 to over 90% (Dronninglund site). The solar fraction[26] achieved by the solar installations coupled to the PTES of Denmark range between 40% and 50%.

1.2.4 Mine Thermal Energy Storage

The idea of storing thermal energy from an inoperative colliery has already been pursued for a long time, although there has been comparatively limited implementation. Before the HEATSTORE project no pilot plants which considered thermal energy storage in a former colliery had been established.

Well-known executed projects concerning the utilization of mine water include:
- The Mijnwater-project in Heerlen (Netherlands), whereby an already completely flooded and no longer accessible mine layout was accessed through directional drilling technology.
- The building of the School of Design at the Zeche Zollverein in Essen (Germany), which is heated by 28°C warm mine water, originating from the mine drainage of the RAG AG.
- The utilization of mine water of the former Robert Müser colliery in Bochum (Germany) as an energy source for the heat supply of two schools and the mine drainage station in Bochum. Within this pilot plant the 20°C warm mine water, which originates from the mine drainage of the RAG AG from a depth of -570 m, is being used.
- Seven operational mine water utilization plants in Saxony (Germany), which can be categorized as shallow geothermal reservoirs. A deep mine water project is currently being implemented at the West Saxon University of Zwickau, where mine water from a depth of 625 m below ground with a temperature of 26°C is planned to be extracted.

In contrast to the Mijnwater-project in the Netherlands, the mine water table in the majority of the central and northern Ruhr area of Germany was much deeper. With a depth of approx. 700 m below the surface this is considerably deeper, with water temperatures of up to 28°C, the energetic expense of the lifting is too high compared to the thermal energy obtained.[27] One way of increasing the efficiency is to increase the temperature of the mine water through the storage of seasonal heat in the mine layout, which has not been realized yet.

Within the Ruhr area and similar areas in Europe, unutilized mining infrastructures in combination with available unutilized surplus heat from power plants and industrial processes, resemble a vast potential for large heat storage capacities. In the case of a technical and economical implementation of the MTES, the design and operation results of the seasonal heat storage within an abandoned hard coal mine, would be scalable to other locations in Germany, Europe and worldwide.

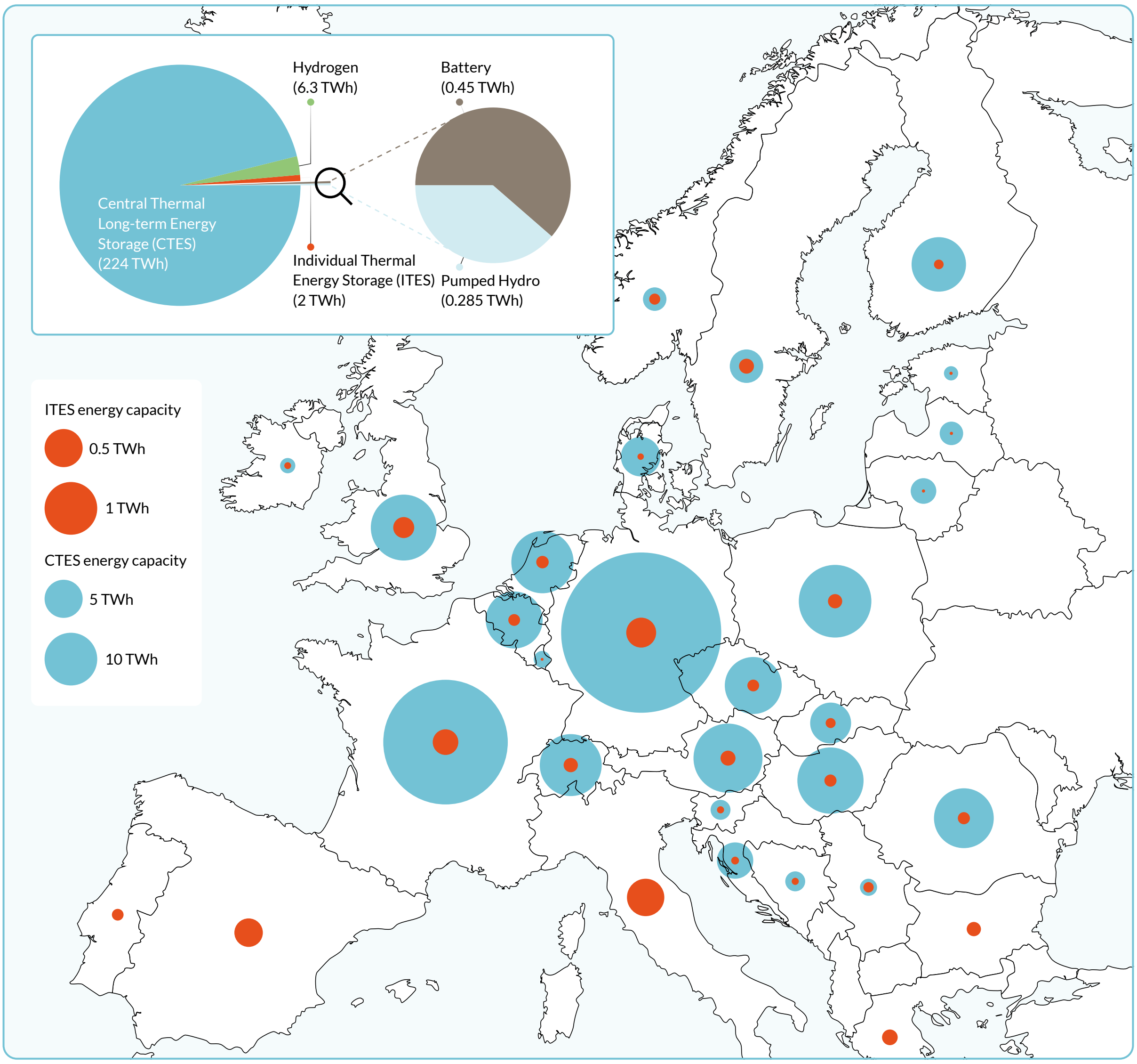
1.3 Role of underground thermal energy storage in a sustainable energy system - a vision for 2050

District heating could be a cornerstone of the decarbonation strategy of the EU, and in order for the district heat networks to be as sustainable, flexible and economically viable as possible, large-scale HT-UTES is part of that promise. However, very limited studies have been performed which evaluate the potential role of HT-UTES in sustainable European energy scenarios.

The study by Victoria et al.[28] is one of few scenario studies for the European energy system that includes thermal energy storage as part of the solution space to provide flexibility. The study includes both individual (small scale) and central long-term thermal energy storage systems in their optimization model to investigate the storage requirements in the future decarbonized energy system. Their results indicate that a large-scale thermal storage (224 TWh) can play a very important role in the heating sector of countries where district heating plays a key role (Figure 9). With that it provides very large flexibility potential to the heating sector to smooth the seasonal profile of heat demand and could even dwarf the role of hydrogen (6.3 TWh)[29], pumped hydro (285 GWh) and battery storage (455 GWh) in Europe in a low carbon future.

In the Heat Roadmap Europe 2050 the European District Heating sector evaluated the feasibility of increasing the use of renewable sources and district heating networks in the future.[30] A truly ambitious scenario is to supply 50% of the heat demand through district heating networks. In that case the heat supply from district heating increases from 602 TWh/year to 1096 TWh/year.[31] More than 600 TWh of this total is then supplied with sources with a continuous profile (geothermal, waste incineration), intermittent profile (heat pumps, electro-fuel production heat recovery) or

Figure 9 Energy storage capacities required in a future European energy system scenario with 95% CO_2 emissions reduction.
Source Victoria et al. 2019.[28]



even with a seasonal offset (solar thermal). Assuming that 10% (see textbox) of the 600 TWh of the baseload or non-dispatchable heat is supplied via storage then 80 TWh of storage capacity is needed. This equals 4000 large-scale HT-UTES projects in Europe by 2050. Obviously, these first order estimates should be confirmed with a European scale integrated energy system scenario modelling adjoining EU's energy transition ambitions and policies.

Overall, thousands of low temperature UTES systems have been implemented across Europe. For the near future the advanced integration of low carbon heat sources in the energy system implies that **hundreds to even thousands of large-scale HT-UTES systems also need to become operational in Europe in the next thirty years** in order for the European heating and cooling sector to contribute to the sustainability goals of the Paris agreement and EUs Green Deal.

The HEATSTORE project has made significant contributions to improve the technology and market readiness of the concepts. It has yielded some important lessons learned and has identified important actions that are needed to further accelerate the development and deployment of HT-UTES across Europe. These are summarized in the following chapters according to the key development themes for HT-UTES technologies:

- Technology & Innovation
- Market & Economics
- Society & Environment
- Policy & Regulations

Geothermal heat and HT-UTES – a strong combination

Geothermal heat as a renewable source for district heating grows from the current ~ 2 TWh/year to 111 TWh/year in 2050.[32] In principle, every geothermal system could and should be coupled to a HT-UTES system in order to maximize the use of the geothermal system and increase the sustainability and flexibility of the heating network. A rough estimate gives us that about 10% (range of this estimate is between 9-15%) of the heat supply is provided by stored heat.[33] This would require the installation of more than 700 large-scale HT-UTES projects of 20 GWh storage capacity.

PTES and sun collector system in Dronninglund, Denmark. Source: NIRAS

HEATSTORE vision on the role of Underground Thermal Energy Storage in the European energy system

- Underground thermal energy storage has the potential to overcome short and long-term mismatch between demand and supply and therefore support the energy system by providing flexibility and adequacy in a sustainable way.
- The application of HT-UTES helps solve the problem of seasonal mismatch in heat supply and demand and can reduce the carbon footprint of the energy sector. The application is widely applicable in energy infrastructures supplying sustainable and low carbon heat to industry, agriculture and district heating grids. Additional benefits of storing heat underground, although technology dependent, help reduce the spatial footprint of the future energy system at surface level.
- Compared to other storage techniques, HT-UTES can store heat over long periods of time (seasons), is economically feasible and compatible with many renewable energy sources. An especially interesting synergy is possible when heat and electricity sources with low marginal cost are available (e.g. geothermal, solar thermal, waste heat, environmental heat with heat pumps). It is an environmentally friendly storage technique which requires a low use of rare earth materials.

- In order to make HT-UTES a success, the development of a strategic portfolio of demonstration sites and a mature regulatory framework as well as a positive public opinion are crucial. This will help develop HT-UTES towards a standard technology for new sustainable energy infrastructures.
- HT-UTES has then the potential to become the largest heat storage option and become an integrated part of the energy system in large parts of Europe. This entails that hundreds to even thousands of large-scale HT-UTES systems need to become operational in Europe in the next thirty years.

‘The advanced integration of low carbon heat sources in the energy system implies that hundreds to even thousands of large-scale HT-UTES systems also need to become operational in Europe in the next thirty years.’

Drilling process of the HT-ATES wells in Middenmeer, the Netherlands. Source: ECW Energy

2. Technology & Innovation

2.1 Gain skills and experience

Learning by doing is the best way to gain skills and improve the knowledge base. For this purpose, demonstration sites with extensive research programmes are key to develop HT-UTES technologies.

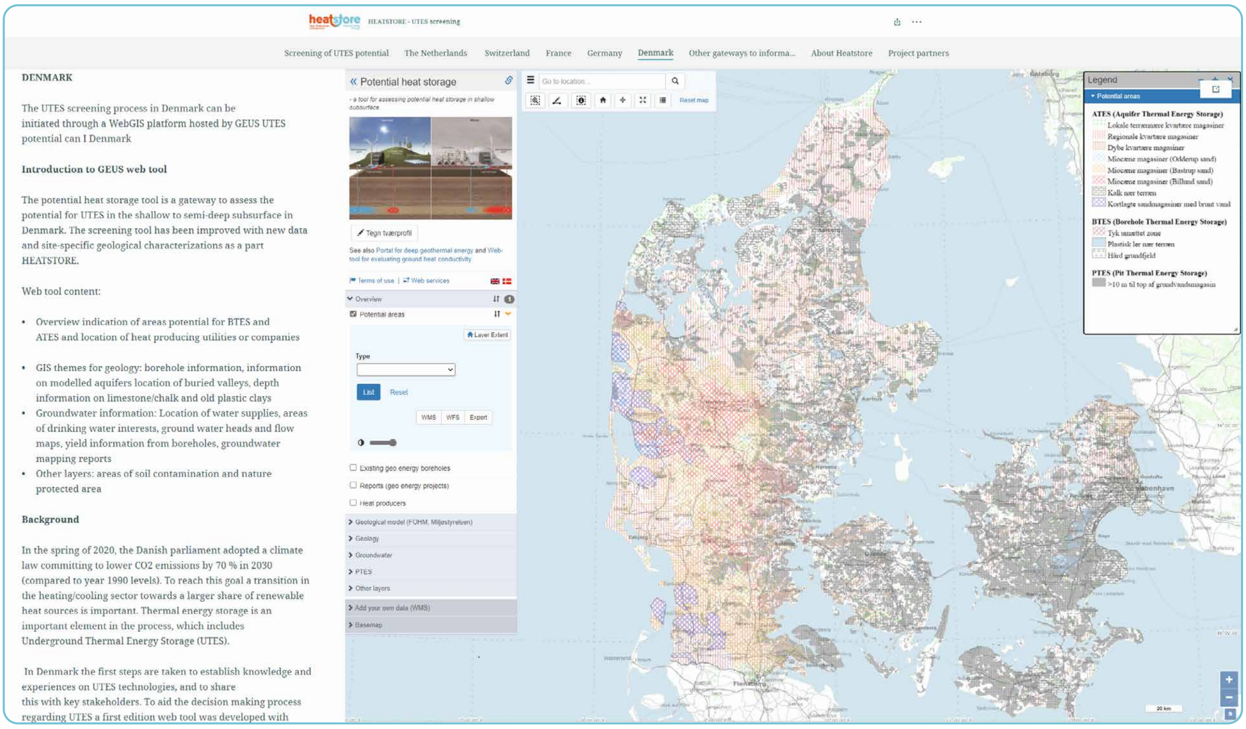
The HEATSTORE programme proved that demonstration sites are crucial to ensure that tested technologies can be brought to market and valorised by the relevant stakeholders.[34] Learning by doing is key. For example, in Denmark the PTES system is brought to operation successfully, and in the Netherlands the first commercial HT-ATES system is currently operational. The factsheets in 'Appendix HT-UTES factsheets' give an overview of the experiences, lessons learned and challenges per HT-UTES technology.

The demonstration sites in all countries contribute to fundamental knowledge and experience, using the gained skills and monitoring data to select the most cost-efficient design and strategy and reduce CAPEX and OPEX of future HT-UTES systems. However, the (sub)surface conditions are highly variable between (and within) the countries, and therefore more demo sites are required to build a broad knowledge base and bring all HT-UTES from TRL 6-7 to TRL 9. Although some countries continued their research in national programmes, it is crucial that at least 15 new (large-scale) demonstration and technology transfer projects will be started in the EU before 2025, in order to enable bankable commercialization before 2030.

HEATSTORE served as a starting point for collaboration and knowledge sharing between European countries. During the project many successes and failures in design, permitting, monitoring plans and project execution were shared. The story map (Figure 10), for example, contains an extensive collection of potential maps for UTES and is publicly available. To accelerate the development of HT-UTES, also monitoring data, continuously updated lessons learned and (software) tools should be shared in one open-access EU knowledge platform.

> ‘The demo sites in all countries contribute to fundamental knowledge and experience.’

Figure 10 The HEATSTORE story map[35] is a web platform that presents and distributes subsurface screening results and map themes to support stakeholders in the investigation into Underground Thermal Energy Storage (UTES) potential. An example of Denmark is shown.



Having the relevant stakeholders on board in future research projects is essential for a successful and efficient demo programme. However, to bring HT-UTES technologies from demonstration and early-commercial to full commercial applications, it is important to learn from existing techniques in other sectors to resolve manufacturing and operational issues. For example, from the oil, gas and geothermal sector for drilling deeper, horizontal or radial wells, and to handle higher pressures and temperatures. In addition, it is important to learn from the construction sector regarding insulation solutions for PTES such as the development of improved liner materials and concepts for top insulation. Knowledge from countries outside Europe also must be applied to these technologies.

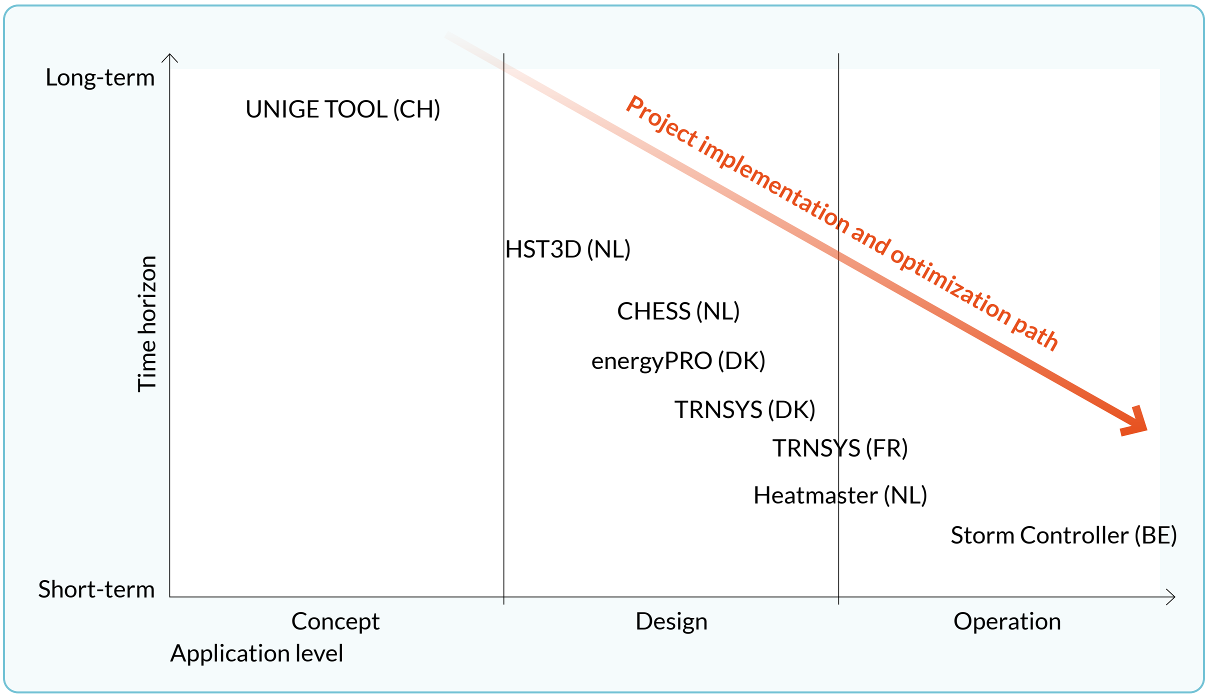
2.2 Integration of HT-UTES in heat grids

Any HT-UTES needs optimal integration in the heat grid in such a way that it improves the flexibility and sustainability of the heat network and increases its cost-efficiency.

In HEATSTORE, the self-learning STORM-controller for optimization of demand side management is brought to a TRL 9[36] and can reduce the heat demand by 15-20% during prolonged peak loads. Model results[37] also showed that a lower return temperature of heat networks will considerably decrease the cost price of the stored heat.

Furthermore, the use of digital twins helps to achieve better design and business cases of HT-UTES systems. In HEATSTORE different software and tools have been developed (Figure 11). The CHESS and Heatmatcher software for design optimization and operation of smart thermal grid concepts are integrated and an ATES module is added. Additionally, several geothermal simulators, like SEAWATv4, COMSOL, compass and more were compared and tested in HEATSTORE[38]. In the Dutch WarmingUP project further development of these tools, all combined in a heat network design toolkit, is currently taking place.[39] Improvement of digital twin software will help the smart integration of HT-UTES in heat grids. An important extra step that has to be taken to be able to fully integrate HT-UTES in heat grids is the optimization of high temperature heat pumps and HP co-designing with HT-UTES. This could bring value to the HT-UTES business case and could offer substantial flexibility to the electricity system and grid. In addition, it is important to have real test cases with data and future projects to test this. Therefore, more industry partners are needed in EU projects to demonstrate HT-UTES systems.

Figure 11 Mapping of the different software and tools according to the time horizon and application at the demonstration sites. Source: HEATSTORE[40]



2.3 Reduce subsurface uncertainty by data acquisition and mapping

An improved insight in the subsurface suitability for the different HT-UTES technologies will lower the threshold for spatial planning agencies and heat network developers to include HT-UTES as part of their energy system.

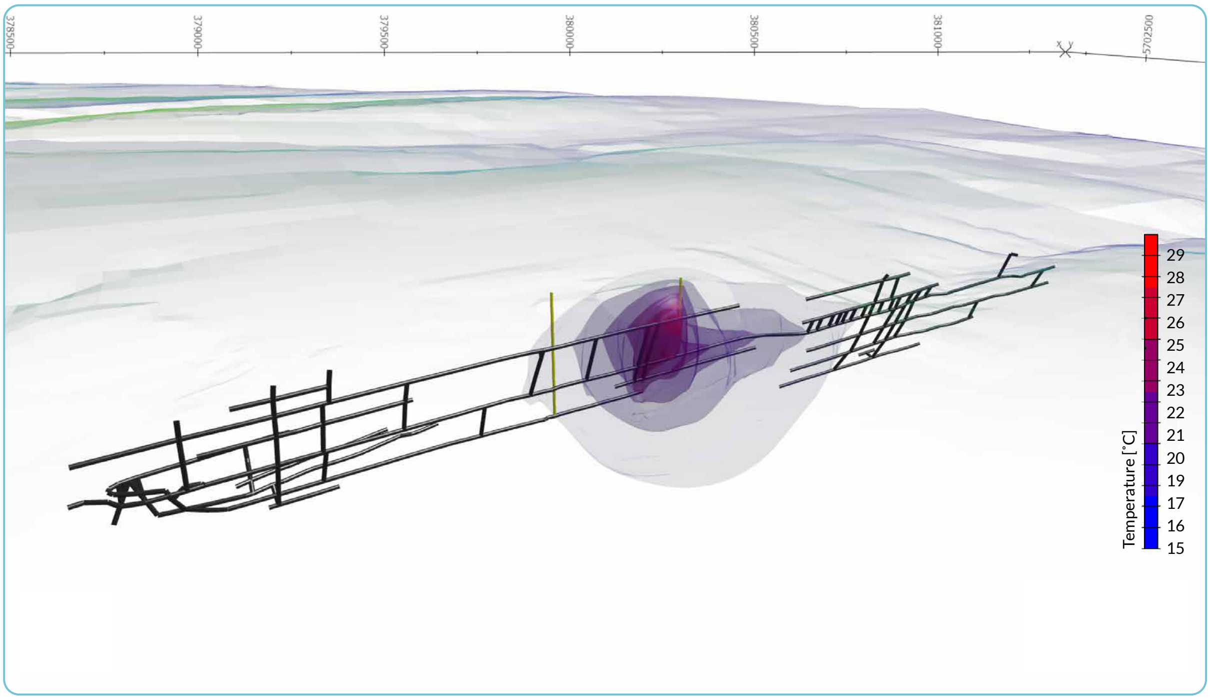
The HT-UTES subsurface potential maps created by each country and collected in HEATSTORE[41] present a broad overview of the feasibility of different HT-UTES technologies in European countries. The maps and storyline clearly show that there is still a need for more and more detailed (sub)surface data. Many countries could benefit from data collection, smart data integration and new data acquisition to develop detailed geological models and reduce uncertainty of subsurface suitability for HT-UTES systems.

Surface data is also needed in many cases to gain insight into the overall potential of establishing a HT-UTES system, for example a better overview of local potential surplus heat producers and heat demands connected to the geological storage potential. Further compilation of geospatial data and the development of an openly accessible platform, as demonstrated in HEATSTORE, show that large-scale mapping activities will unlock the full potential and integration of HT-UTES. In areas with sparse data coverage, seismic reprocessing of the shallow subsurface can reduce the uncertainties.[42] New demonstration programmes will provide monitoring data and lab test results to validate models, and further develop the subsurface models for HT-UTES. It will also define boundary conditions for subsurface storage, which can help to improve potential maps.

Besides optimized data processing, mapping and modelling of the subsurface, new low-cost subsurface data acquisition solutions are needed. For example, a low-cost test drilling would reduce uncertainty in the subsurface and therefore reduce project risks, and it would be a valuable addition in between full scale test drilling (that could escalate to above 100,000 euro) and subsurface modelling. This is especially valuable in areas with low data density or quality.

> 'New demo programmes will provide monitoring data and lab test results to validate models, and further develop the subsurface models for HT-UTES'

Site-scale thermal modelling of MTES system. Source: delta h Ingenieurgesellschaft[43]



2.4 Improve efficiency of HT-UTES

Improved efficiency of a HT-UTES in the (first) operational years will enhance the business case and lower the financial risk.

Both HT-UTES models and operational HT-UTES systems generally show a low efficiency in the first years of operation (Figure 12), related to the heat loss to the relatively cold surroundings. Smart operational control of HT-UTES can help to overcome this problem, for example, by using free surplus heat to optimize the efficiency in the loading years. Overall efficiency can also be improved by optimizing well design and configuration of the system. In HEATSTORE a start has been made with this, however, more demonstration sites are needed to fully understand the best practice with respect to optimization and to validate design calculations and calculation tools by monitoring activities and evaluation of performance and efficiency of HT-UTES systems.

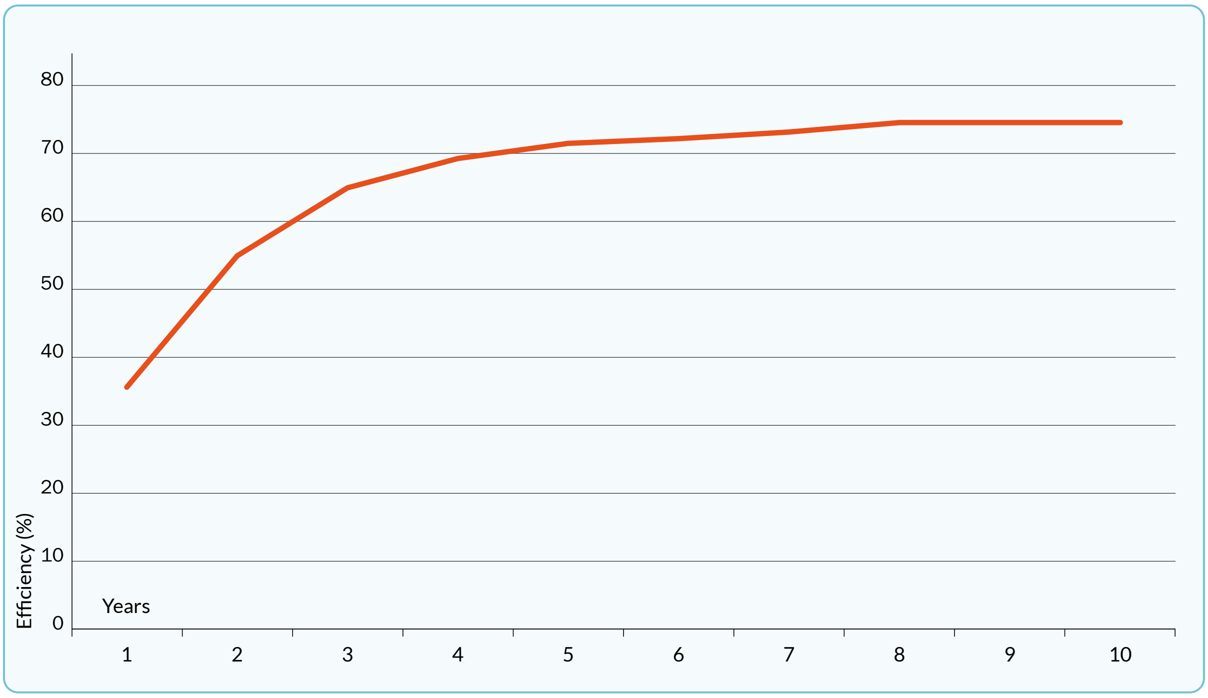
In HEATSTORE, sustainable materials and equipment were analysed for their capacity to maximize the lifetime of HT-UTES. For example, a glass fibre reinforced epoxy liner for HT-ATES[44] is found to be robust and will extend the lifetime of high temperature wells. Also, for the PTES technology, lifetime can be extended by application of new insulation and liner materials. For instance, a new lid solution has been developed for the PTES in Marstal. It relies on a multi-layer lid including a polyethylene foam designed to withstand temperatures up to 100°C.[45] At the PTES of Høje Taastrup, a new kind of liner material is used, and it can withstand a constant temperature of 90°C.[46] Storage specific technology and innovation targets are listed in the HT-UTES specific factsheets at the end of the document.

2.5 Reduce operational risks

Reduced operational risks will increase investment incentives and the feasibility of the system.

Operational risks need extra attention. Examples of these operational issues are corrosion and scaling in the piping system, heat exchanger and wells as well as damage to surface equipment for HT-ATES, or insulation risks for PTES. HEATSTORE results show that the main operational risks for HT-UTES are related to water chemistry (scaling, corrosion) and its effect on system materials (well and surface equipment/heat exchanger materials).[47]

Figure 12 General example of HT-UTES efficiency over a 10-year period showing low efficiency in the first operational years.



Analysis of scaling in heat exchangers and wells is needed to reduce operational risks. Scaling prevention, for example with CO_2 injection, needs to be further investigated together with the knowledge on well pressures, water treatment and materials.[48] This can be done with lab tests, regular monitoring and model validation of the existing and new/planned demo programmes. With the standardization of materials and methods, the development of HT-UTES projects will accelerate due to an easier workflow and cost reduction.

‘With the standardization of materials and methods, the development of HT-UTES projects will accelerate due to an easier workflow and cost reduction.'

Surface facility equipment for the geothermal installation at Middenmeer, The Netherlands. Source ECW Energy

PTES and sun collector system in Marstal, Denmark. *Source: Aalborg CSP*

3. Market & Economics

3.1 Follow a structural approach to establish a robust business case model

Every underground thermal energy storage project is unique, but a common approach can help to establish a robust business case

A successful business model for HT-UTES projects has several important components that should all be tuned depending on the specific location and project conditions. In that sense every project is unique but within the HEATSTORE project we learned that a common approach (Figure 13) can help to establish a robust business case model for HT-UTES in the early phase of project development.

3.2 Improve storage economic project fundamentals – CAPEX and OPEX reduction

Learning-by-research, by-doing and by-replication will drive down investment and operating cost of HT-UTES technologies

A key insight observed within the HEATSTORE project and in literature[49] is that large-scale thermal storage solutions can be more cost-effective than electricity storage and the storage of hydrogen. This is shown in Figure 14 and Figure 15 where the specific investment costs and storage efficiency are shown. To place these

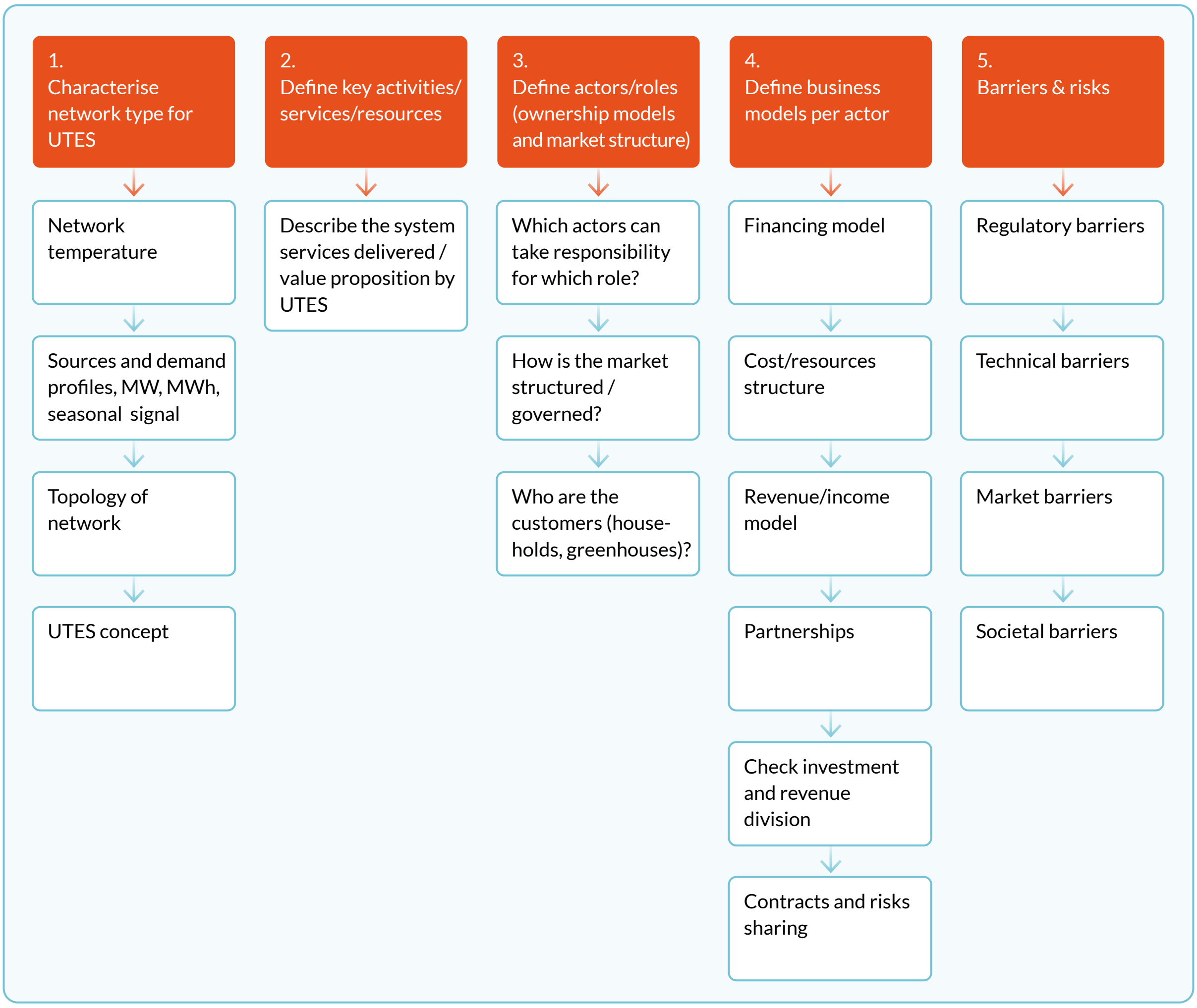


Figure 13 Recommended HEATSTORE approach to establish a business case for HT-UTES projects.[50]

numbers in perspective; the optimistic target for battery electricity storage lies at approximately 100 € / kWh_{vol}[51], with efficiencies for li-ion batteries ranging between 80-96%.[52, 53] For longer duration storage with Compressed Air Energy Storage (CAES) technology the investment lies approximately at 50-150 eur/ kWh_{vol} with an efficiency of 55%[54]. Hydrogen storage is typically one of few seasonal storage alternatives to HT-UTES and its specific investment costs ranges between 0.2-0.9 € / kWh_{vol} with an efficiency of almost 100%[55].

Another important economic indicator for storage options is the Levelized Cost Of Storage (LCOS) which is typically defined as the total lifetime cost (investment and operational cost) for an energy storage technology divided by its cumulative stored and delivered energy (e.g. heat, electricity, hydrogen. Levelized cost of storage for HT-UTES ranges between 0.05-0.15 € / kWh_{LCOS}[63]. However, it should be noted that for HT-UTES there is a lack of LCOS estimates in literature and that LCOS values depend very strongly on local project conditions for HT-UTES projects; including the

Figure 14 Specific investments costs (upper) and round trip storage efficiency (lower) of several HT-UTES technologies in comparison with hydrogen storage in caverns and tank thermal energy storage (TTES).[56, 57, 58, 59, 60, 61, 62, 63] *Note: HT-MTES is not included due to lack of data.*

type of HT-UTES technology, subsurface conditions, temperature level, price of stored heat, storage efficiency, size, financing parameters and utilization/ cycling rate per year. The basic cost of establishing and operating an HT-UTES facility, form an important pillar in a sustainable business model for HT-UTES projects.

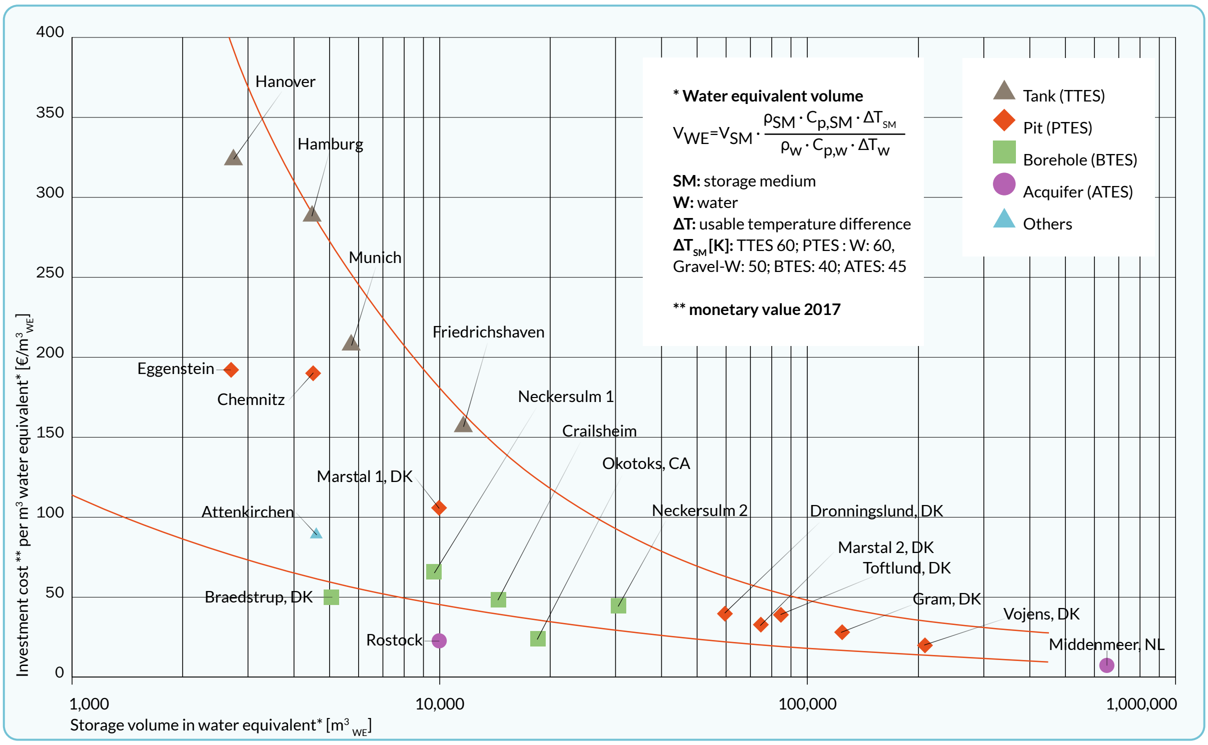
Within the HEATSTORE project valuable and important lessons have been learnt regarding the cost of HT-UTES projects. The investment costs are technology and project specific but roughly show an noticeably high share for subsurface drilling, wells and pumps (see Figure 16 for investment cost break down for HT-ATES facility at ECW, the Netherlands). For the PTES technology the pit, insulation material and lid are important parts of the investment. For BTES the drilling costs may account for approx. 50% of the total construction costs; the top insulation typically represents 25%. Surface level equipment is a considerably smaller part of total CAPEX but certainly not to be neglected. The operational costs are strongly affected by purchasing the heat for loading (and the heat loss penalty after unloading) and by the operational costs of the pumps (electricity and maintenance/replacement costs).[64]

Denmark is a front-runner for PTES connected to district heating systems and key lessons have been learned to reduce costs and improve performance. For low temperature ATES the Netherlands, Sweden, Denmark and Belgium are countries with ample experience and also HT-ATES is advancing in the Netherlands. Also HT-BTES has been successfully deployed within Europe. MTES is currently remains lower on the technology readiness scale. All technologies have their own specific cost reduction opportunities as these often lie in improving materials selection and components cost reduction. As well as optimising the design of the HT-UTES facility to fit within the heat network and broader energy system at the specific location.

Important actions to reduce overall project cost are:

- Developing new and establish experience with applying low cost materials for HT-UTES. Examples are high temperature resistant liners for PTES and low-cost high temperature resistant well and pump cost reduction for ATES.
- Improved modelling, design and integration of HT-UTES in the heat network and energy system to better size and fit the system with the energy system needs. This also supports improving the storage efficiency of HT-UTES projects
- Develop industry standards in material selection and design procedures for HT-UTES systems; first of a kind projects typically include wide safety margins in the design resulting in high engineering and design costs as well as high component costs.
- Learning curve cost reductions: replication of projects with similar conditions opens up cost reduction in the supply chain for HT-UTES projects as components and realisation costs decrease due to increased experiences.
- Reduce subsurface risks with enhanced publicly available data of the subsurface across the EU and reducing drilling risks for the HT-UTES project developer.

Figure 15 Specific storage cost of UTES demonstration plants. Including all necessary costs for building the storage device, without design, without connecting pipes and equipment in the heating plant without VAT. Source: Solites



3.3 Create and stack business model revenue opportunities

Together with actors in the value chain define system services and value propositions by HT-UTES in early phase of project development to maximise the revenues

As with other energy storage technologies it is critical to get the revenue pillar of the business model right. This is achieved by matching a revenue model for the value that a storage project provides to the system and to individual actors in the value chain. In the HEATSTORE project we found that value proposition evolves around (but is certainly not limited to):

- Security of heat supply for customers
- Applying surplus and locally produced heat at low cost
- Delivering low carbon heat supply to customers

Revenue is dominantly influenced by time-value of heat sales, but is very case specific and heat sales is certainly not the only prospected revenue (monetary and non-monetary) for HT-UTES projects. The shown example projects in HEATSTORE indicate value stacking of value propositions adding to a potential positive business case. Moreover, it shows that HT-UTES projects have site specific value propositions and thus require an approach to identify and valorise these propositions. In many situations the revenues are not sufficient and thus requires (policy) incentives to achieve a positive business case. Figure 17 shows an overview of possible value propositions for the HEATSTORE HT-ATES project at Middenmeer, the Netherlands.

GRE (Glassfibre Reinforced Epoxy) well casing for the HT-ATES in Middenmeer, The Netherlands. Source: ECW Energy

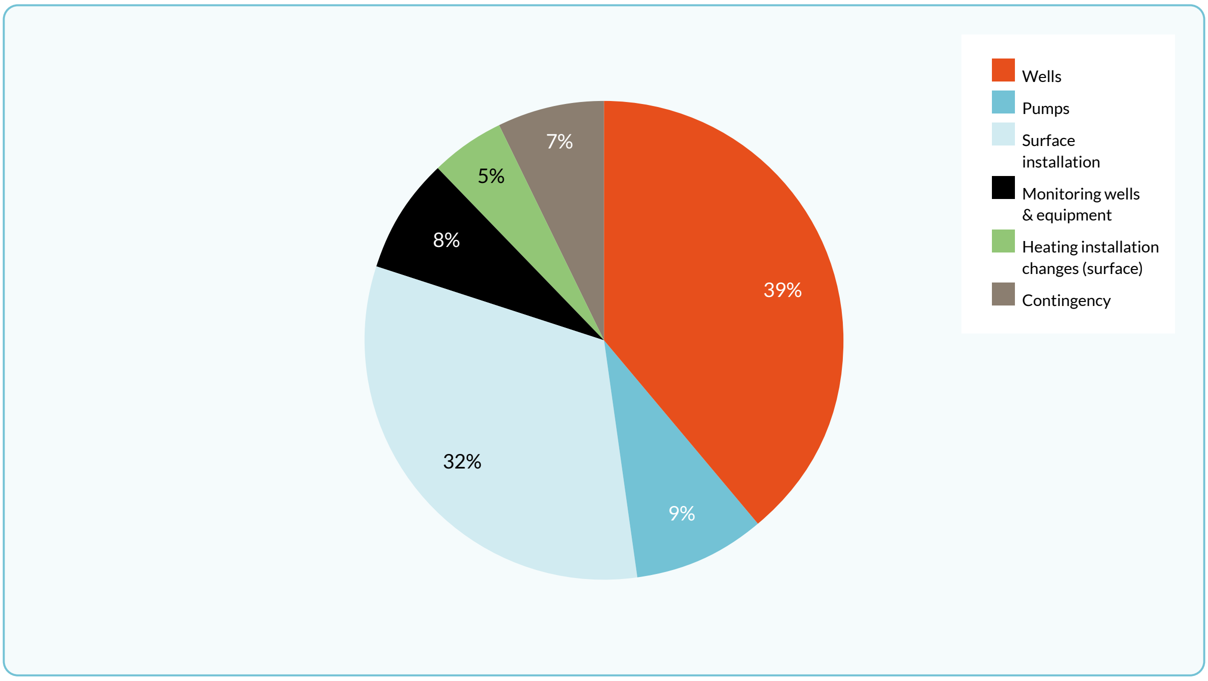
Actions required to optimize revenue and develop a sustainable business case:

- Define system services and value propositions by HT-UTES in early phase of project development for all actors involved in the value chain.
- Develop new combinations of revenue streams and business models
- Share best practices for stacking of revenue streams for HT-UTES projects across the EU
- Identify areas for replicating business models opportunities for synergies

On the longer term this could open up opportunities to:

- Combination of storage and conversion options (hybrid storage and flexibility options including HT-UTES technologies)

Figure 16 Investment cost breakdown for HT-ATES facility in Middenmeer, the Netherlands.[50]



3.4 Transparent ownership and market player relationships

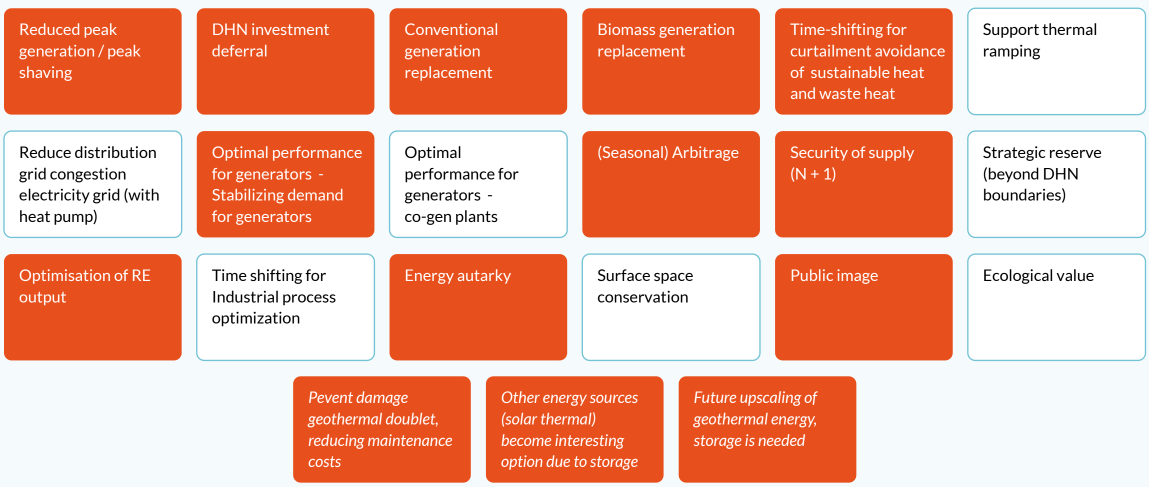
The ownership model and market structure shape the business model for HT-UTES projects

In Europe there is a large diversity between market structures and market regulations for heat networks. And even within countries heating networks are differently regulated and structured. This typically has a large impact on the regulation of pricing, third party access, consumer protection, investment support, economic regulation and private and or public (municipally) ownership models.[65] HEATSTORE also found that the value chain consisting of key partners, resources (including heat sourcing) and customer segments vary considerably per country and heat network configuration. This is of high importance for HT-UTES implementation as the HT-UTES project requires capturing multiple value propositions (value stacking) to deliver a sustainable business case. This is believed to be easier captured as the system value and cost of implementing HT-UTES in a heat network (i.e. the sum of all value propositions) is fairly distributed over the actors (e.g. producer, transport network operator, consumer, storage operator) in the heat network. This requires clarity of roles and responsibilities and to find ownership and contractual relationships between partners that optimally fit with the business case.

Proposed actions:

- Evaluate system level value of HT-UTES integration in heat infrastructure
- Define the sharing of risks and benefits between the actors in the value chain (e.g. by using the business model canvas)[66]
- Share best practices on ownership options and market relationships under different type of market structures
- Try different type of business case structuring for different types of ownership configurations

Figure 17 Value proposition for UTES projects, the value propositions that apply to the HT-ATES demonstration project in Middenmeer are highlighted in red. In summer, heat from geothermal systems is stored in the HT-ATES.[67]



In this example the possible combination of value propositions is shown for the HT-ATES project at Middenmeer in the Netherlands while highlighting two important and prospective monetized value propositions:

- More geothermal heat in the mix as summer surplus is being utilized with low marginal cost of production
- Stable geothermal operation (flat rate vs. seasonal pattern) – reducing geothermal operational costs by reducing pump maintenance cycles and stress reduction in the geothermal system due to temperature and flow variations

4. Society & Environment

4.1 Evaluate, mitigate and monitor environmental impacts

Guidelines to evaluate and mitigate environmental impacts and robust monitoring programmes will support containment of risks.

Some environmental effects related to HT-UTES systems are inevitable; the local extraction and injection of groundwater and the thermal perturbations induce per definition physical, chemical and microbial changes. The impacts include:

- Hydrogeological effects; groundwater flow related to changes in the hydrologic equilibrium;
- Flow around the wells, mixing of water and corresponding changes in groundwater quality;
- Reservoir thermal effects and extent of heating zone;
- Soil mechanic effects related to changes in hydraulic head and to thermal expansion or shrinkage;
- Changes in physical properties of the aquifer due to temperature changes;
- Changes in groundwater chemistry and quality related to temperature changes, and the corresponding risks for pollution;
- Changes in microbial populations related to temperature changes.

The environmental impacts are highly case- and location specific and need to be evaluated in the early phase of an HT-UTES project in a dedicated risk assessment, using numerical or analytical models, and expert opinions. In case of insufficient data for adequate decision making, test sampling should be considered. An overview and description of the different types of environmental impacts, and an evaluation of the impacts for the demonstration sites is developed as part of the HEATORE project.[68]

Undesirable impacts may be prevented by adapting the design of the system. The prevention options are also highly case and location specific. In the case that undesirable impacts cannot be prevented, or the required design to do so is too expensive, the investigated storage technology/formation is not suitable.

Robust programmes, based on cost-efficient tools, are needed to monitor the performance of a HT-UTES system and any applied prevention measures and (remaining) environmental effects and risks. In addition, monitoring data is essential for model validation and calibration, and can be used in data assimilation workflows to improve performance prediction and operational control. Thermal effects, including spatial distribution of the heat, buoyancy effects and heat losses can be measured by various different techniques such as Distributed Temperature Sensing (DTS) in wells, Electrical Resistivity Tomography (ERT), acoustic measurements and pulse testing. The groundwater chemistry and microbial activity can be monitored by frequent downhole sampling and sample analysis. InSAR data or Distributed Accoustic Sensing (DAS)/ Distributed Strain Sensing (DSS) give information on ground movement. Several of these techniques have been applied and demonstrated at the demonstration sites of the HEATSTORE project. A robust comparison of technologies, application under various subsurface conditions and an evaluation of environmental impact monitoring on long-term operation of HT-UTES systems is still strongly advised. The suitability and cost-efficiency of the different techniques need to be defined for the different HT-UTES technologies and guidelines for a suitable monitoring design are required. Fit for purpose monitoring programmes have therefore been developed within HEATSTORE e.g. for microbiological and chemical water quality analysis and temperature distribution. For the NIOO-KNAW pilot site in the Netherlands it was possible to reduce obsolete parts of monitoring in order to have a more focussed programme on the key aspects of interest. This optimized monitoring programme has been implemented in the relevant site.[69]

Proposed actions:

- Learn from ongoing monitoring programmes at operational HT-UTES systems;
- Develop guidelines for the evaluation and mitigation of environmental impacts of the different HT-UTES technologies;
- Develop cost-efficient monitoring tools and fit-for-purpose monitoring programmes.

> ‘ Robust monitoring programmes are needed to monitor the performance of a HT-UTES system and any applied prevention measures and (remaining) environmental effects and risks.

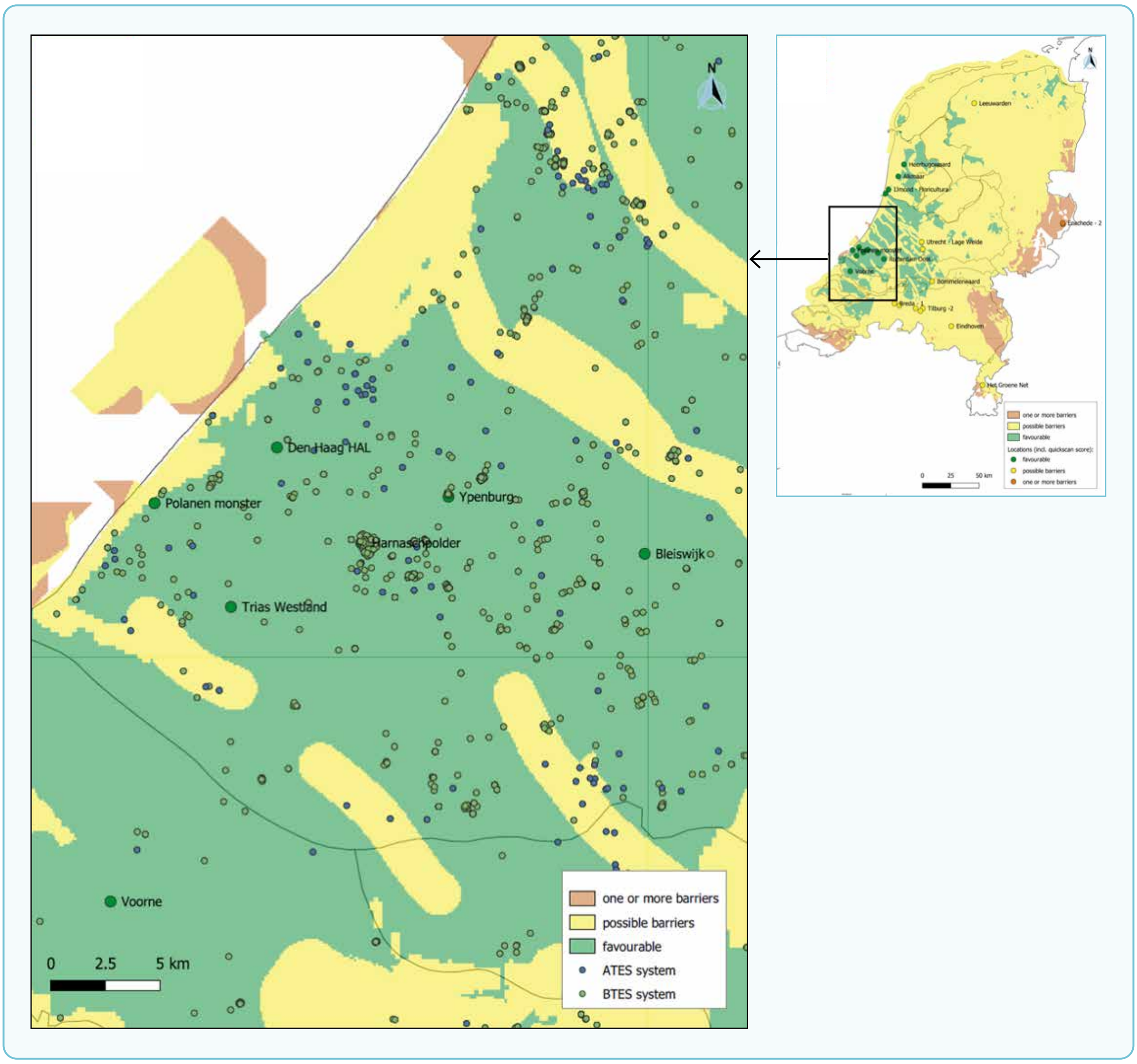
4.2 Solid spatial planning for subsurface

To govern competition of subsurface space, spatial planning for the subsurface is essential.

The subsurface, which traditionally has been used for activities such as archaeological activities, underground building, pipeline networks, drinking water extraction, CO_2 storage and various mining purposes (including oil & gas, coal, salt), has recently been subjected to activities related to the energy transition, such as geothermal energy extraction and CO_2 and various types of energy storage. The multifunctionality of the subsurface is promising but it can also create conflicts in case of competing uses[70] (Figure 18). Since subsurface space is limited, its use should be sustainable, safe and efficient and it should be treated integrally and as a very valuable resource.

A close interaction exists between the use of the surface and the subsurface. Surface infrastructure is needed for subsurface activities. In urban areas, the required subsurface activities are defined by the spatial use and developments of the surface area at the local or regional scale. Yet, the (hydro)geological and geochemical characteristics of the subsurface are key in defining the possibilities for its use as the different subsurface activities can only be applied under highly specific subsurface conditions. The impacts of subsurface activities cannot be easily reversed. This implies that the choices that we make restrict the possibilities for the future. It is therefore essential to

Figure 18 Low temperature ATES and BTES systems in the Dutch subsurface. The zoom shows the densely populated area in the western part of the Netherlands, where the potential for HT-ATES is high (green) and several projects are initiated (green dots with city name). However, some HT-ATES project locations might interfere with existing systems. Source: Dinkelman et al. (2020).[71]



consider future developments and their implications for subsurface requirements[72].

A HT-UTES system requires, besides the space for surface facilities, a claim on subsurface space that can generally not be used for other applications. The space involves the area that is impacted by the temperature perturbation, within the storage aquifer, around the hot well and in the over- and underlying geological layers. Induced groundwater flow could affect an even larger area, but might not necessarily limit subsurface use in those regions. The risk of groundwater contamination in overlying aquifers through leakage along the well requires consideration, especially when it concerns (potential) drinking water resources.

HT-UTES systems need to be developed in areas where excess heat is available and a flexible heat source is required to optimize the heat supply and demand. Specifically, regions with existing or soon to be developed district heating networks would highly benefit from HT-UTES systems. Since heat transport is inefficient and costly, HT-UTES systems need to be developed close to, and strategically placed, within the area of the district heating network. Note that innovative, smart integration of sustainable subsurface technologies, e.g. heat/energy storage or geothermal energy production with CO_2 as working fluid[73], could reduce the required subsurface space and limit competition.

Strategic planning for the subsurface needs to be supported by clear policies and regulations on a national scale.[74, 75] In each country, the responsibilities of the different activities in the subsurface are organised in a different way. Often, the various activities are accommodated at several different local, regional or national administrations or authorities. Collaboration and coordination between the public administrations, but also with the private landowners, is needed in the development of a solid spatial planning. Coordination at an early stage and at national level is crucial alongside support at EU level, for example by developing best practices based on European HT-UTES systems.

Actions:
- Proactive local/regional/national spatial planning in subsurface: reserve space for HT-UTES

4.3 Create social awareness and support

In order to build trust and engagement among stakeholders, including the public, it is important to create awareness in HT-UTES development in general and in an early stage of HT-UTES projects specifically.

In general, the public is becoming more and more involved in societal activities such as sustainable technology implementation and people are increasingly critical when it concerns activities that impact them, either directly or indirectly. It is recognised that the general attitude towards (new) technologies can be very different from local attitudes towards a specific project.[76] The so called 'not in my backyard' attitude is highly persistent once a given project/technology has acquired this status. Local opposition to an otherwise positively perceived technology may have a seriously negative impact on the implementation of sustainable technologies, including HT-UTES. In order to achieve stakeholder support a cohesive and timely involvement strategy for local stakeholders should be part of the formal decision-making process[77]. Demonstration sites that have a national or regional role in public information are instrumental to facilitate public acceptance.

In the HEATSTORE project the involvement of stakeholders was analysed for 11 UTES cases and geothermal systems[78]. Based on this study, the main public concern for UTES technologies involves the economic risk and potential negative impact on groundwater and drinking water quality. Concerns regarding the impact on groundwater and drinking water can often be eliminated by the implementation of a fit-for-purpose monitoring system. Studies performed in Denmark showed that investments in renewable energy technologies can come from small communities taking pride in being active in lowering their carbon footprint.[76] Overall support for renewable energy technologies turned out to be highly beneficial. The creation of general awareness of HT-UTES as crucial component of a future sustainable heat supply, and early local stakeholder engagement in specific HT-UTES projects are both needed for successful, large-scale deployment of HT-UTES.

Proposed actions:
- Communication isis crucial! Create early general awareness of HT-UTES and build trust by showing lessons learned from demonstration and early projects
- Facilitate early engagement with stakeholders and involvement of the public for specific HT-UTES projects
- Develop social engagement programmes
- Promote benefit of local heat solutions

5. Policy & Regulations

5.1 Create a joint vision on HT-UTES

To increase awareness and create a good strategy for adoption and governance, HT-UTES should be placed higher on the political agenda.

Relative to the decarbonisation of the European electricity supply, limited attention has been paid to the decarbonisation of the heating and cooling sector.[79] By showcasing the crucial role of thermal storage in the future energy system and presenting a joint vision on the importance of HT-UTES on a National and European level, HT-UTES technologies can benefit from the attention of policy makers and gain a higher position on national and European agendas. This can be realised by developing extensive (national) heat roadmaps with clear financial incentives and the political ambition to realise these. For this purpose, the establishment of a dedicated European alliance for HT-UTES technologies consisting of knowledge partners and industrial and regulatory stakeholders is highly recommended. Such an alliance which could also be used for knowledge sharing, should support and advise the European Technology & Innovation Platform (ETIP) Smart Network for Energy Transition (SNET) on the integration of HT-UTES technologies in sustainable and flexible district heat networks.

Due to its large technological variety and the spatial dependency of HT-UTES applications it is important to promote regional solutions instead of international dependency, whilst still maintaining a clear national and European vision.

A valuable next step would be to include HT-UTES in energy and climate strategies of cities (see text box), industry clusters, regions, member states (e.g. in future National energy and climate plans and long-term strategies) and Europe requires awareness and capacity building among stakeholders at different geographical levels and across industry, science, governments and the public.

‘The establishment of a dedicated European alliance for HT-UTES technologies consisting of knowledge partners and industrial and regulatory stakeholders is highly recommended.’

District heating needs flexibility to navigate the energy transition

(source IEA)[80]

“Cities and districts are in a position to lead the energy transition, often setting more ambitious targets than their national counterparts, as district energy networks provide the infra-structure for greater energy security and renewable energy integration. District heating can be linked to electricity systems through co generation of electricity and heat, and through power to heat production in large-scale heat pumps.“

5.2 Provide clear regulatory framework

Clear regulations specifically for HT-UTES technologies need to be developed to promote the large-scale adoption of HT-UTES.

The HEATSTORE research programme studied existing regulatory frameworks of a selection of European countries (Netherlands, France, Switzerland, Denmark and Germany), identifying existing regulatory frameworks and potential barriers.[81] The most restricting and recurrent barriers that were identified are the low maximum temperature and the strict regulation for maintaining thermal balance in the subsurface. This complicates the operational strategy of a storage system. Other barriers include: stacking of regulations, lack of a long-term development plan, no supporting policies and absence of thermal regulations in the built environment. Additional concerns are the lack of experience of local, regional and national authorities which results in complex and slow permit procedures.

These issues can be resolved by creating a clear timeline for the permit application and formulating fit for purpose reporting demands and permit criteria. A successful example can be seen in the Netherlands for the low temperature (LT-)ATES technology (<25°C), which is a proven and successful technique that has been applied for years. As a result the procedures for permitting, designing, realizing and exploiting these systems are well-established. This enables further implementation of the technique, although the procedures still need to be adapted to HT-ATES.

With respect to thermal regulation of heat it is important to set up a legal framework on waste heat recovery and for authorities to apply an integrated approach to licensing of heating and cooling technologies.

5.3 Adapt policy to HT-UTES: support programme to lower financial risks

HT-UTES projects are an integral part of large and long-term infrastructure investment decisions that require investment certainty for project developers. Simple and clear support schemes and an enabling market framework are required to support stakeholders in the development of HT-UTES systems.

HT-UTES projects have typically long lead times to move from project idea to effective operation of the system, i.e. typically longer than modular storage technologies. And they are part of thermal networks which have operation horizons of decades. This requires long-term investments, but at the same time there is often unclarity on the policy and market evolution over this timeframe.

'In general, fossil fuel subsidies or low tax rates limit the incentives for stakeholders in European countries to invest in decarbonisation options in general and HT-UTES specifically.'

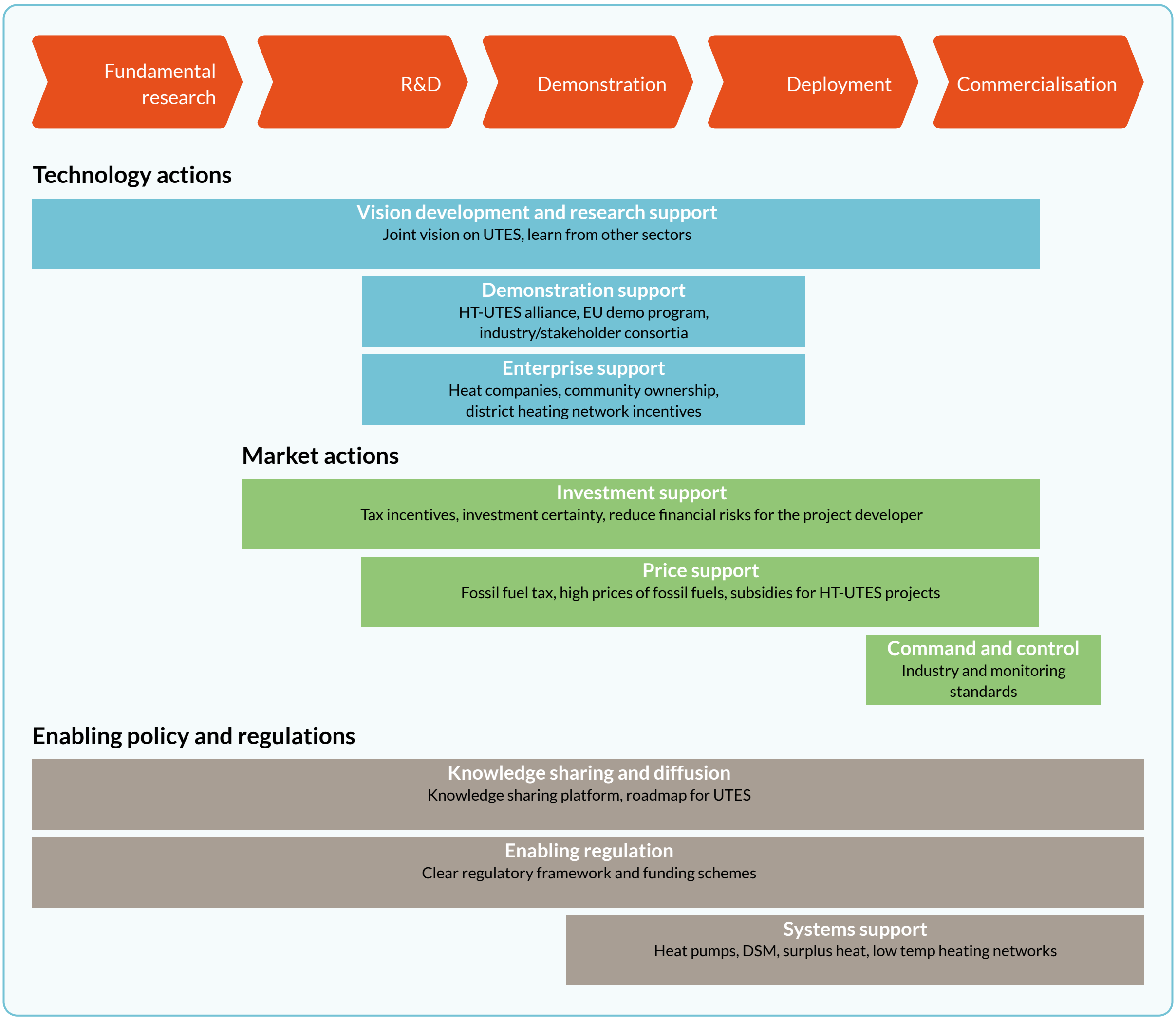
For early commercial HT-UTES projects financial risks for project developers are large. Within HEATSTORE we have seen cost escalations for specific projects, delays in project execution (time to market), and a remaining uncertainty of project operational performance and cost escalations (e.g. operational costs and efficiency). Subsidies allow projects to be economically feasible for the stakeholders. This stresses the need for subsidies in early phases of technology implementation when early movers (pioneers) cannot benefit from best practices. This highlights the need for continuous technology development to bring down costs, but also a supportive market framework that offers favourable conditions for a sustainable business case.

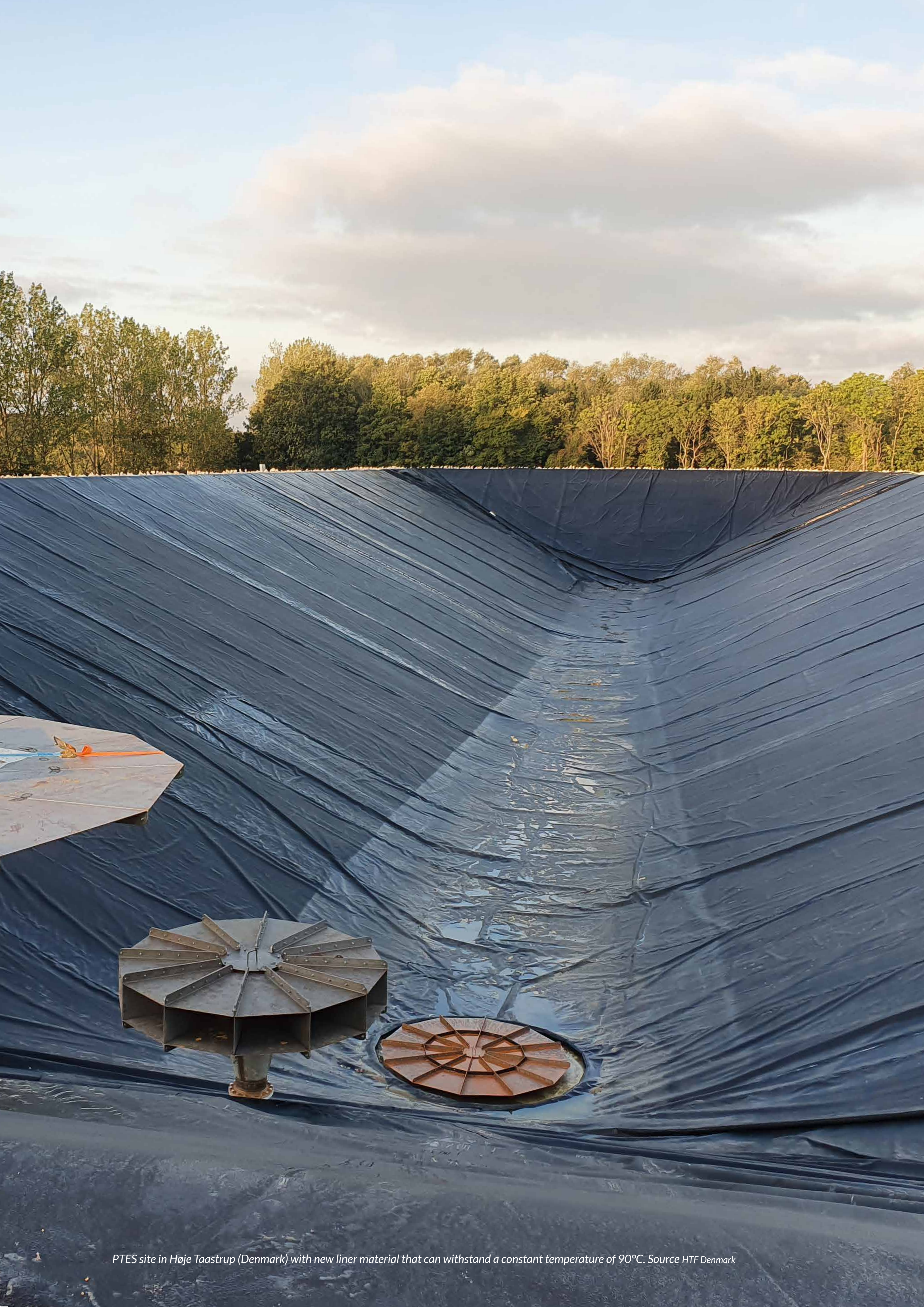
Such a supportive framework should aim at decreasing financial risks for project developers and operators. It should reduce both risks of cost escalation of project development (e.g. CAPEX subsidies) and operational risks (e.g. OPEX subsidies, contract for difference, feed-in tariffs, performance based risk fund). Project developers should be challenged to develop a robust and flexible operational strategy to also cope with risks in early commercial projects.

For the community of heat network developers, storage project developers, operators and shareholders a long-term investment certainty of system transformation is needed. For HT-UTES projects to become successful a beckoning perspective and market design is needed for the next decades that entails a strong and secure push for low carbon heat sources (geothermal, solar, heat pumps, waste heat utilisation) and adequate phase-out of fossil fuels (including financial and tax supports). As this market design is highly state specific, we suggest that market design best practices should be shared and replicated across Europe acknowledging that such market design transformation can take many years to implement.

In general, fossil fuel subsidies or low tax rates limit the incentives for stakeholders in European countries to invest in decarbonisation options in general and HT-UTES specifically. This issue can be addressed by creating a fair CO_2 price. A combination of technology push, an enabling framework and market pull support such as investment support, the commercial competitiveness of HT-UTES technologies can be increased which will help these technologies to advance (Figure 19).

Figure 19 Actions for HT-UTES to develop the technology from fundamental research to commercialisation. Adapted from: IRENA.





PTES site in Høje Taastrup (Denmark) with new liner material that can withstand a constant temperature of 90°C. Source HTF Denmark

6. Key messages

The need for progress and inclusion of thermal storage in a comprehensive approach to energy storage has recently been highlighted by the European Parliament.[82] A clear recognition that demands further actions in the short and longer term. Considering that the timeline from project idea up to an operational system spans several years, large-scale adoption of this technology should start now. Specifics in geology and surface restrictions may provide better conditions for specific HT-UTES technologies and exclude others. Therefore, a portfolio of HT-UTES technologies needs to be available and be technologically advanced to enable location specific needs to be identified and addressed. This requires urgent action.

6.1 Strong need for awareness and strategy on local, national and European level

Despite its magnitude and importance in the European Union's energy markets, the heating and cooling sector is overlooked in energy transition scenarios and policies. Especially for HT-UTES, limited studies have been performed which evaluate the potential role of these storage technologies in sustainable European energy scenarios. A focus is typically applied on electricity and hydrogen storage options in most recent EU scenario studies while overlooking the vast storage potential HT-UTES technologies may provide at competitive costs.

The integration of HT-UTES in a heat network with sustainable heat supply contributes to increasing the efficiency of renewable and low carbon energy sources. Additionally, HT-UTES adds much needed operational flexibility and security of supply to energy systems at large as part of a storage technology portfolio servicing different energy capacity, time dimensions and energy grids.

The integration of HT-UTES technologies in future energy scenarios and energy system planning demonstrates the crucial role that HT-UTES needs to play in the decarbonatization of the heat sector. This supports the development of local and national roadmaps for a sustainable heating and cooling supply.

Including HT-UTES in energy and climate strategies of cities, industry clusters, regions, countries and Europe requires awareness and capacity building among stakeholders at different geographical levels and across industry, science, governments and the public. The local and regional governments are key entities as heating and cooling networks span across their jurisdiction. This also requires early local public stakeholder engagement in specific HT-UTES projects for successful, large-scale deployment of HT-UTES. And when included in a robust communication and engagement strategy towards all relevant stakeholders, this will be a crucial support in the creation of awareness.

It is key that the European technical storage potential for HT-UTES technologies is assessed, preferably based on publicly accessible subsurface data provision. Within HEATSTORE the potential for HT-UTES is assessed in several countries to highlight location specific potential. The role of HT-UTES in the transitioning energy system towards 2050 and beyond should be assessed allowing to quantify regional, national and European market potential for HT-UTES technologies and pinpoint promising areas for HT-UTES technologies. From this location specific market opportunities and project proposition can be developed leading towards a project development portfolio across Europe. Proactive spatial planning of the subsurface is a prerequisite to reserve (subsurface) space for HT-UTES technologies and start early awareness across stakeholders. For example, as part of member states' National Energy and Climate Plans.

'Including HT-UTES in energy and climate strategies of cities, industry clusters, regions, member states and Europe requires awareness and capacity building among stakeholders.'

6.2 Help early movers with financial de-risking and support scheme for early commercialisation

To grasp the promising potential for HT-UTES technologies in Europe, the technology and market readiness level should be elevated further. This requires technology development to bring down costs and also a market framework that offers favourable conditions for a sustainable business case.

Specific components of HT-UTES technologies have been identified that show opportunities for further cost reduction. Moreover, cost reduction can be achieved by scale-up (economies of scale), by replication (learning by doing) of the technology and by optimized integration in the heat network.

For early commercial projects, the financial risks for project developers are high to bear. Reducing uncertainty in technological performance or cost escalation during project built or operation would drive the different HT-UTES technologies faster towards commercial implementation. After a proven set of HT-UTES flagship projects, the technologies will become more competitive and bankable. Until this period, a support and risk reduction scheme for HT-UTES technologies is needed to be installed at member state level. Best practice examples are risk funds for geothermal heat projects that cover technology performance risks that are inherently coupled with uncertainties in subsurface conditions to store heat. Subsidy schemes for operational costs, feed-in, contract for difference arrangement and support packages alike could be brought into place to support the technology. It is critical to find a balance between de-risking both the investment and operational project costs. Lessons from the past show the importance of supporting technologies after the initial investment phase.

6.3 Launch the European Underground Thermal Energy Storage Alliance

The HEATSTORE consortium proposes the start-up of an alliance that secures the upscaling of HT-UTES across Europe. We suggest to launch the European Underground Thermal Energy Storage Alliance as part of the mission to bring Europe to the forefront of HT-UTES technology development and valorise the market

Surface installation of the HT-ATES in Middenmeer, the Netherlands with connection to the heat network. *Source: ECW Energy* potential that HT-UTES technologies have in the future EU energy system. This public-private Alliance will bring together industry, research & innovation institutes and (local/national) governments from member states.

- A European HT-UTES alliance can play a key role, in the development of both the national roadmaps and the communication strategy to build stakeholder awareness and strategy.
- Such an alliance will provide a platform for knowledge and experience sharing from HT-UTES flagship projects as started in HEATSTORE and for similar Research Development & Innovation (RD&I) programmes. A portfolio of at least 15 new demonstration and technology transfer projects need to be started before 2025 to enable bankable commercialization before 2030.
- To establish the number of sites RD&I efforts need to be increased on thermal energy storage in Europe that matches its large potential to support the decarbonisation of the heating and cooling sector.[83]
- The alliance will help to refine the European Strategic Energy Technology Plan for this family of technologies. It can facilitate RD&I infrastructure sharing across Europe and allow for exchange programmes in the scientific community.
- The alliance can build a repository for long-term monitoring programmes on techno-economic and HSE (Health Safety and Environment) performance of HT-UTES projects.
- Partners of the alliance can together develop and foster standardization and design replication to decrease technology costs and improve performance.
- With this, the alliance builds the environment for further innovation across Europe and can build the local value chains that are needed for HT-UTES technologies to be implemented at a large scale and with high storage quantities. This includes training local engineers, geological surveys, governments, consultancies, local equipment and service providers.
  This will also bring along technology export opportunities that the Alliance can facilitate.
- Finally, the Alliance can bring the needed input to develop a comprehensive framework of regulatory and non-regulatory measures to support HT-UTES technology development and implementation across the EU. The European Green Deal is a perfect landing point for advanced progress in HT-UTES technologies to support the heating and cooling sector in meeting the aim to become the first climate neutral continent.[84]

Figure 20 Overview of MTES demonstration site in Bochum, Germany. Source: Hahn et al. 2019

PTES and sun collector system in Dronninglund, Denmark. Source: NIRAS

HT-UTES factsheets

HT -ATES factsheet

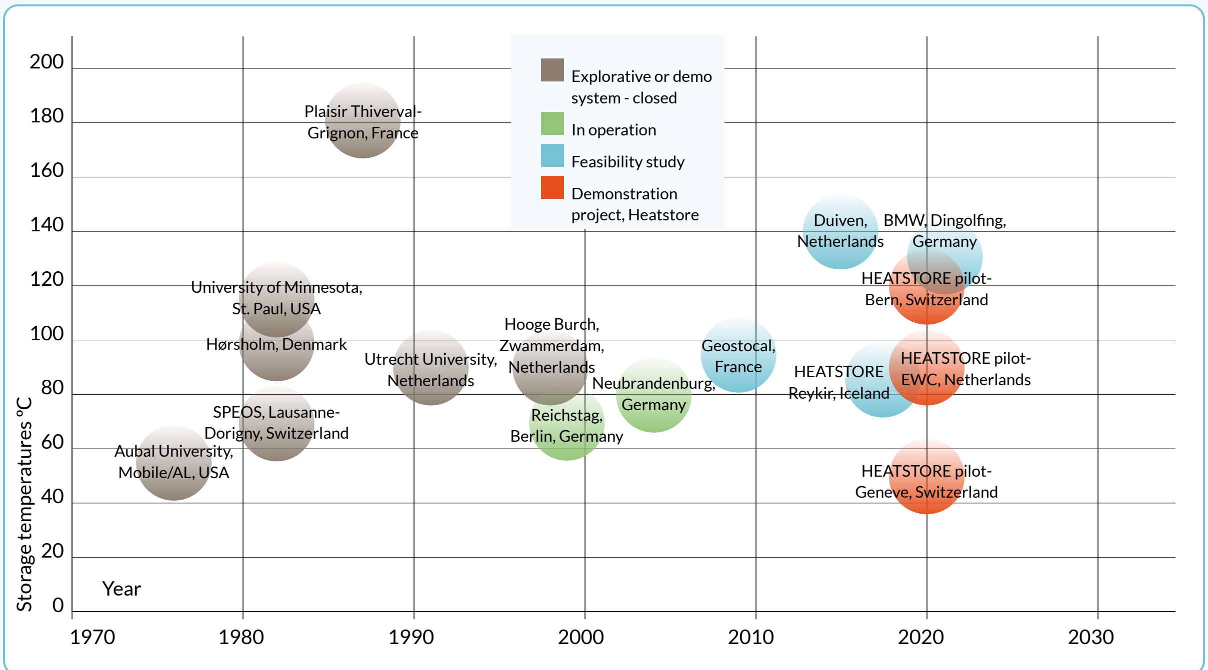
Experience

- Storage temperatures from 50°C to 150°C
- Storage depths: < 100 m to > 1000 m
- 7 closed systems – the first pilot in 1976
- 2 existing systems in operation
- 3 feasibility studies
- 3 planned/under construction (2021)

Lessons learned

- Screening for availability of aquifer/reservoir, infrastructure and potential conflicts of interests is a prerequisite
- Perform a test drilling before the design phase and include pumping tests. Perform a reference measurement on natural groundwater composition
- Perform modelling studies:
  - Thermal transport models to investigate thermal recovery efficiency and thermal effects in the subsurface.
  - Geochemical modelling to research influence on groundwater composition upon heating Geochemistry (water)
- Sufficient permeability is required for efficient production/injection → but too high hydraulic conductivity may cause significant heat losses by density driven groundwater-/heat flow. A confining layer above the heat storage reduces losses to shallow layers.
- Water treatment should be considered at temperatures >50°C, using natural chemical substances like HCl or CO_2.
- Well construction and choice of materials (pumps, casing and screens) depend highly on temperatures and water/sediment geochemistry
- Well capacity (and declining well capacity) needs to be evaluated and not overestimated
- Careful monitoring is highly recommended in order to diagnose and optimize the system
- Repeated re-generation of wells should be implemented in the maintenance budget
- Do visual inspection of well heads, valves, transmitters and heat exchangers for leakage and corrosion as preventive maintenance
- Thermal losses are higher for smaller systems and for higher storage temperatures
- Storage volume of at least 300,000 m^3 of water is recommended
- Demand side requirement of minimum 5 MW thermal power is recommended
- Most efficient if used as base load during unloading
- Important that the entire energy system is fitted to possible temperature ranges in the ATES system: The lower the useable (cut-off) temperature the better

HT-ATES projects since 1970



Challenges

- Maximum injection temperature (20-25°C) in the current regulations is a barrier in some countries
- General lack of clear regulation
- The "geological risk" regarding the aquifer/ geothermal reservoir is significant – the deeper the reservoir, the higher the risk
  - In HEATSTORE TNO has been working on better subsurface characterization through reprocessing of existing seismic data
  - In HEATSTORE ETHZ and other partners have been working on improving models for characterization of reservoir dynamics
- Clogging of fines and calcite scaling are known problems
  - Ca/Na ion exchanges can be used to prevent precipitation of $CaCO_3$, but may cause clay swelling
  - HCl-treatment is effective, but expensive and subject to public acceptance
  - CO_2 treatment may be effective but needs to be tested in practice
- Large initial investment for preinvestigations and modelling

Surface equipment of HT-ATES well in Middenmeer, The Netherlands. Source: ECW Energy

HT-BTES factsheet

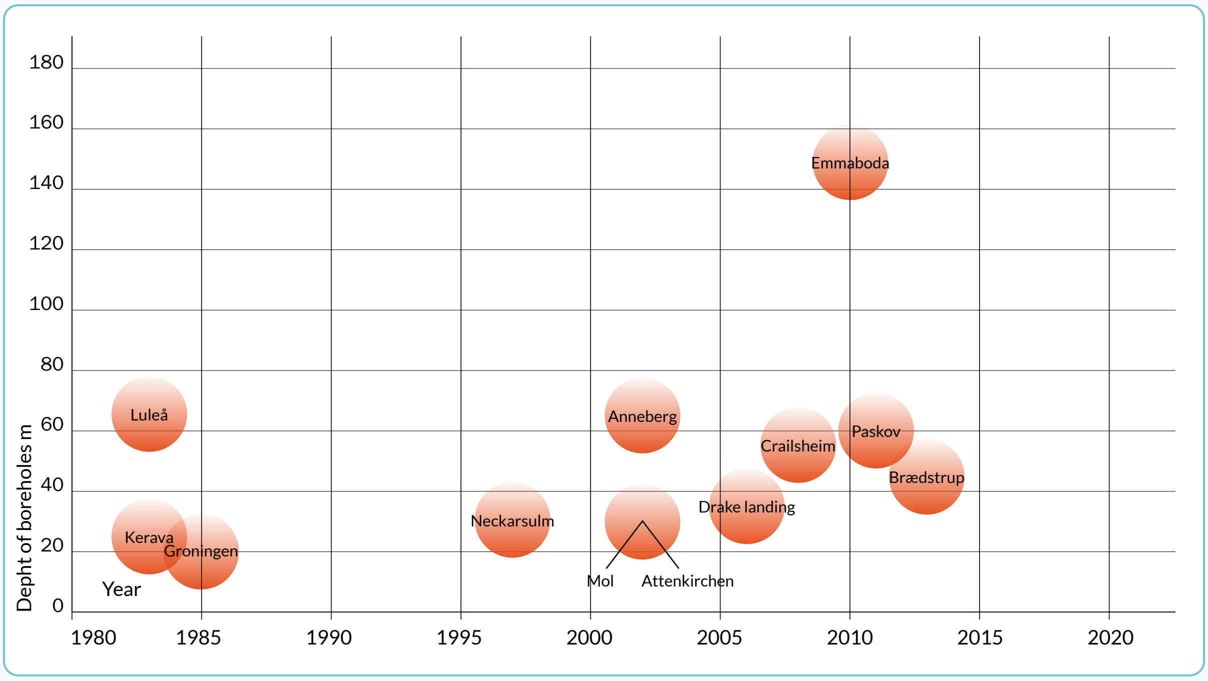
Lessons learned

- Screening for geology, groundwater flow, thermal properties, infrastructure etc.
- Perform a test drilling to verify the ground conditions and the estimated drilling costs and include a thermal response test to verify the thermal properties of the site
- A low thermal conductivity increase the recovery efficiency, but decrease the rate of charging/discharging
- In soft sediments grout sealing of the boreholes is always recommended (and often required) in order to protect groundwater resources and to obtain thermal conductivity in unsaturated conditions
- The drilling costs may account for approx. 50% of the total construction costs
- A top insulation of the BTES is necessary to reduce the heat loss and may account for 25% of the total construction costs
- A BTES reacts slowly during charging and discharging and normally a buffer heat storage like a water tank is necessary, especially if the heat source is solar
- High quality cross-linked high-density polyethylene (PEX) tubes are normally used as they are strong, chemical resistant and can withstand high pressures and high temperatures
- Double U-tubes are found to be more efficient than single U-tubes
- The storage efficiency (where known, 45% - 60%) is often lower than expected/modelled
- In general, a start-up period of a few years should be expected to heat up the storage and the surroundings
- the specific costs drop significantly with increasing storage size and in general BTES systems larger than 20,000 m^3 of storage volume are recommended
- There is good business case for BHE systems for seasonal heating and cooling of buildings and there are several hundred of systems in Europe – but for heat storage alone, BTES can be an expensive solution, especially if a high thermal power is needed
- Large initial investment for drilling and top isolation
- A clear regulative framework is missing in many countries
- Risks of not getting a permit and/or a long permit procedure
- In HEATSTORE STORENGY is transforming an existing, but depleted (too cold), BHE system into a BTES for surplus heat storage

Experience

- 12 existing systems
- Closed loop system using soil/bedrock volume as storage media
- Storage temperatures from 45°C to 80°C
- Storage capacities from 100 to 3800 MWh

HT-BTES projects realized since 1980.



Challenges

- There is good business case for borehole heat exchanger (BHE) systems for seasonal heating and cooling of buildings and there are several hundred of systems in Europe – but for heat storage alone, BTES can be an expensive solution, especially if a high thermal power is needed
- Large initial investment for drilling and top isolation
- A clear regulative framework is missing in many countries
- Risks of not getting a permit and/or a long permit procedure
- In HEATSTORE STORENGY is transforming an existing, but depleted (too cold), BHE system into a BTES for surplus heat storage

Drilling of BTES facility in Braedstrup, Denmark. Source PlanEnergi

HT-PTES factsheet

Lessons learned

- Soil properties/geotechnical parameters must be checked in order to utilize the excavated soil as banks
- Groundwater flow is unwanted in order to prevent heat loss from sides and bottom and avoid bank instability
- Relatively large space requirements
- The top of the banks must be levelled, and the excavated soil must be compressed when rebuilt into the banks
- Plastic liners and insulating lid is critical elements for the performance
- A floating lid is the cheapest, but most sensitive option
- Must be tight and dry and with no air pockets below and rainwater must be drained from the top
- Temperature monitoring from bottom to top in the storage is necessary for optimization of operation
- Water quality must be checked and filters cleaned at regular intervals
- Check the construction by diver inspection and check for leakage and wet insulation
- Check regularly for wet insulation to avoid heat loss
- Environmental Impact Assessment - Screening is required
  - Permission for seepage of groundwater drainage and drainage water from lid-top is necessary
  - Permission for seepage/drainage of (salty) return water from softening unit when filling storage
  - Permission for new water supply drillings for water to fill storage (can be very time-consuming)

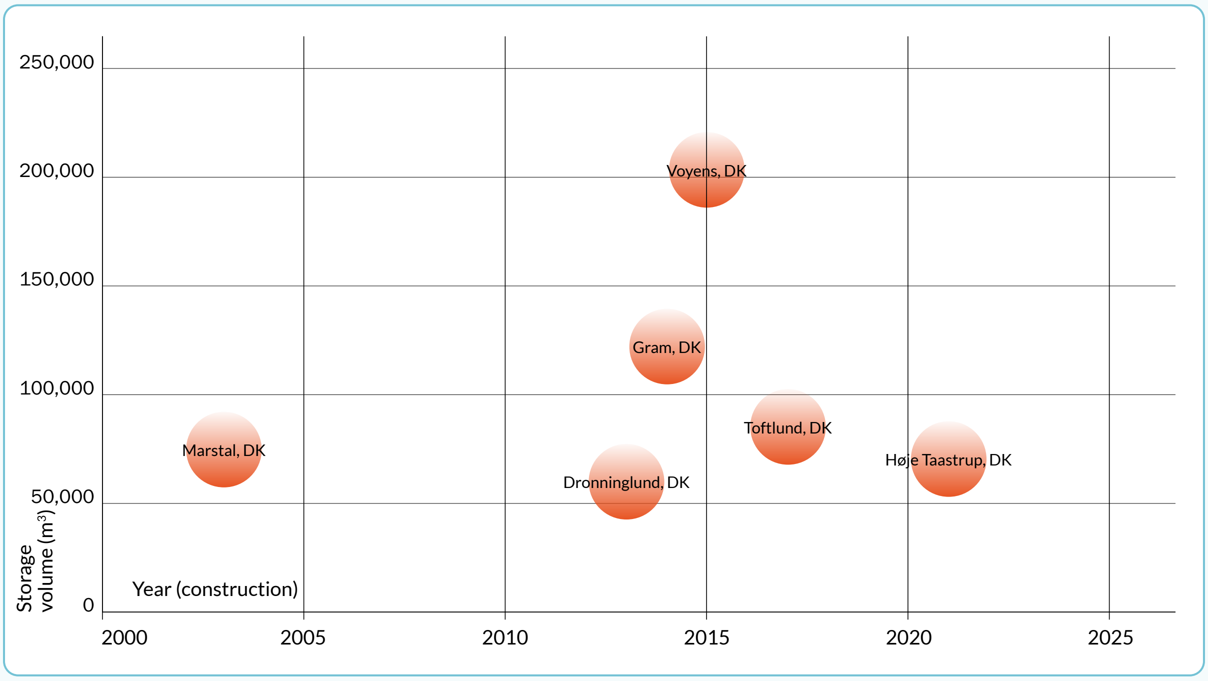
Experience

- Pit storage is using water as storage media
- 6 existing systems in Denmark
- More systems planned
- Storage temperatures up to 90°C
- Storage volumes 60,000 m³ to >200,000 m³
- Storage capacities from 3000 to >12,000 MWh
- Storage efficiency up to 60-90%
- Effective for both short- and long-term storage
- High charge- and discharge capacity

Challenges

- Large space requirements – not ideal in urban areas
- Straight forward, but time-consuming permit procedure
- Generally, very successful systems with recovery efficiencies up to 60-90%
- One PTES system has experienced a leak from the basin which could be repaired after the unloading period
- Rainwater lakes/water ponds on the top lid can be a problem
- Some PTES systems has experienced problems with leaks in the insulating lid and wet insulation material
- In Denmark, focus in recent years has been to improve the construction of the lid
  - Sectioned lid constructions
  - Layering of insulation material
  - Better materials

HT-PTES projects since 2000.



HT-MTES factsheet

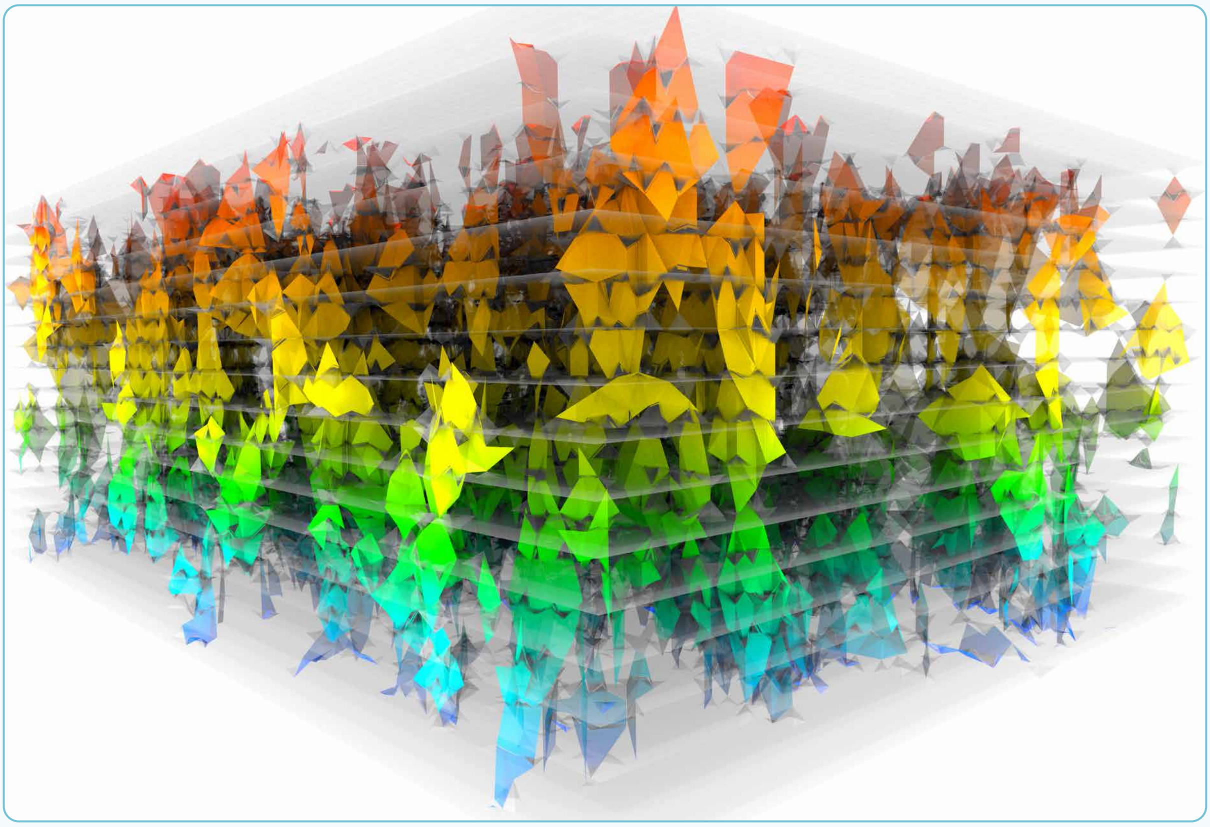
Lessons learned

- No mine water heat storage has been realized so far
  - Within the Ruhr area, abandoned and flooded mine infrastructures in combination with available surplus heat from power plants and industry provides a vast potential for large-scale heat storage
  - Pilot project in HEATSTORE: Small colliery below the premises of the Fraunhofer IEG in Bochum
- A large mine water volume, safe and close to a district heating network is needed
- Information on mine layout, depth and condition
- Modelling of hydrology, thermal impact and hydro-geochemistry coupling the mine hydraulic and thermal behaviour to the surrounding rock mass and aquifers
- Permit procedure can be complex

Experience

- Mine water of abandoned and flooded mines has until now only been used as low-temperature energy source for heating buildings and a few plants exist in Germany and the Netherlands, for example he Mijnwater-project in Heerlen (Netherlands) at 28°C

Figure 12 High detail model of stochastic generated fracture sets to estimate local effects, like the influence of fractures, on hydraulic conductivities in a MTES system. Source: delta h Ingenieurgesellschaft mbH



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Please cite this report as: Roadmap for flexible energy systems with underground thermal energy storage towards 2050, HEATSTORE 2021, GEOTHERMICA – ERA NET Cofund Geothermal.

This report represents HEATSTORE project deliverable number D6.4

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Design: KNOEFF Communication Design